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# FINAL TECHNICAL REPORT

## For NASA Cooperative Agreement NCC2-926

## "Studies of Mineralogical and Textural Properties of Martian Soil: An Exobiological Perspective"

Period of Performance: October 1, 1995 to June30, 1999

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Research, technical, programmatic, and mission accomplishments for NCC2-926:

- 6 peer reviewed papers
- 37 abstract presented at scientific meetings
- Several workshops organized and chaired
- PI membership of several committees and organizations including "MEPAG", New Millennium Review Board, PG&G Review panel, Ames "FAME" group for missions operations, SOWG for Mars 2001, etc.
- 3 space flights: MECA payload on MSP 2001, EGM payload on Space Station, and ICAPS payload on Space Station via NASA/ESA agreement.

Abstracts are attached to illustrate the diversity, accomplishments, and productivity of the research. No patents were filed from technology research in NCC2-926.

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John Marshall, Ph.D
SETI Institute
2035 Landings Drive
Mountain View, VA 94043-0818

September 1999

# NCC2-926 PUBLICATIONS

(Copies not available at time of report compilation)

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(1) Arvidson, R., Acton, C., Blaney. D., Bowman, J., Kim, S., Klingelhoefer, G., Marshall, J., Nieber, C., Plescia, J., Saunders, R., & Ulmer, C.: Rocky 7 prototype Mars Rover field geology experiments: No.1, Lavic Lake and Sunshine Volcanic Field, CA. J. Geophys. Res. 103, no. E10, 22671-22688 (1998).

(2) Koppel, L., & Marshall, J. A miniature metal-ceramic x-ray source for spacecraft instrumentation. Rev. Sci. Instr. (AIP), 69, no 4, 1893-1897 (1998).

(3) Marshall, J.R., F. Freund, & T. Sauke. Microgravity studies of electrostatic aggregation in particulate clouds, Geophys. Res. Lett., submitted (1998).

(4) Marshall, J.R., F. Freund, T. Sauke, & M. Freund (1997) Catastrophic collapse of particulate clouds: Implications from aggregation experiments in the USML-1 and USML-2 glovebox. NASA TM 1998-208697 (Second United States Microgravity Laboratory: One Year Report, Vol 2, 35/579-35/592.

(5) Stoker, N. Cabrol, T. Roush, J. Moersch, J. Marshall, J. Schreiner, M. Sims, H. Thomas, and Marsokhod Rover Team. Marsokhod Rover Mission Simulation at Silver Lake CA, 1999: Mission Overview. J. Geophys. Res. In press (1999).

(6) R. E. Arvidson, D. Banfield, J. Bell, D. Braun, D. Ferguson, G. Landis, L. Lowry, J. Marshall, A. Mishkin, P. Smith, S. Squyres. Coordinated Science Objectives and Measurement Campaigns Associated With the Mars Surveyor Program 2001 Lander Payloads. 2001 MSP Mission Space Science Reviews. In press (1999).

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# NCC2-926 ABSTRACTS

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### UNIQUE AEOLIAN TRANSPORT MECHANISMS ON MARS: RESPECTIVE ROLES OF PERCUSSIVE AND REPERCUSSIVE GRAIN POPULATIONS IN THE SEDIMENT LOAD MARSHALL

John R., SETI Institute, MS 239-12, NASA Ames Research Center, Moffett Field, CA 94035-1000, jmarshall@mail.arc.nasa.gov

Experiments show that when sand-size grains impact a sediment surface with energy levels commensurate for Mars, small craters are formed by the ejection of several hundred grains from the bed. The experiments were conducted with a modified crossbow in which a sand-impelling sabot replaced the bolt-firing mechanism. Individual grains of sand could be fired at loose sand targets to observe ballistic effects unhindered by aerodynamic mobilization of the bed. Impact trajectories simulated the saltation process on dune surfaces.

Impact craters were not elongated despite glancing (15 deg.) bed impact; the craters were very close to being circular. High-speed photography showed them to grow in both diameter and depth after the impactor had ricochetted from the crater site. The delayed response of the bed was "explosive" in nature, and created a miniature ejecta curtain spreading upward and outward for many centimeters for impact of 100-300 um-diameter grains into similar material. This behavior is explained by deposition of elastic energy in the bed by the "percussive" grain. Impact creates a subsurface stress regime or "quasi-Boussinesq" compression field. Elastic recovery of the bed occurs by dilatancy; shear stresses suddenly convert the grains to open packing and they consequently become forcefully ejected from the site. Random jostling of the grains causes radial homogenization of stress vectors and a resulting circular crater. A stress model based on repercussive bed dilatancy and interparticle adhesive forces (for smaller grains) predicts, to first order, the observed crater volumes for various impact conditions.

On earth, only a few grains are mobilized by a percussive saltating grain; some grains are "knudged" along the ground, and some are partly expelled on short trajectories. These motions constitute reptation transport. On Mars, saltation and reptation become indistinct: secondary or "repercussive" trajectories have sufficient vertical impulse to create a dense saltation population of many tens or hundreds of grains for each single high-speed saltation percussion of the bed. Impact cascading will lead to near-surface distortion of the boundary layer, and choaked flow formed by a dense "slurry" of sand, with the majority of grains mobilized by repercussive forces rather than by aerodynamic lift. This proceeds until a fully-matured transport layer imposes self-limitations as grain-population density constrains the free-path motion of individial grains.

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# *IN SITU* IDENTIFICATION OF MINERAL RESOURCES WITH AN X-RAY-OPTICAL "HAND-LENS" INSTRUMENT

J. Marshall (SETI Institute) MS 239-12, NASA Ames Research Center, Moffett Field, CA 94035-1000 (Tel: 415-604-4983; L. Koppel, Oryx Technology Corporation, Fremont, C. Bratton, SETI Institute/NASA Ames; E. Metzger, San Jose State University, San Jose; M. Hecht, Jet Propulsion Laboratory, Pasadena

The recognition of material resources on a planetary surface requires exploration strategies not dissimilar to those employed by early field geologists who searched for ore deposits primarily from surface clues. In order to determine the location of mineral ores or other materials, it will be necessary to characterize host terranes at regional or subregional scales. This requires geographically broad surveys in which statistically significant numbers of samples are rapidly scanned from a roving platform (1).

To enable broad-scale, yet power-conservative planetary-surface exploration, we are developing an instrument that combines x-ray diffractometry (XRD), x-ray fluorescence spectrometry (XRF), and optical capabilities; the instrument can be deployed at the end of a rover's robotic arm, without the need for sample capture or preparation. The instrument provides XRD data for identification of mineral species and lithological types; diffractometry of minerals is conducted by ascertaining the characteristic lattice parameters or "d-spacings" of mineral compounds. D-spacings of 1.4 to 25 angstroms can be determined to include the large molecular structures of hydrated minerals such as clays. The XRF data will identify elements ranging from carbon (Atomic Number = 6) to elements as heavy as barium (Atomic Number = 56).

While a sample is being x-rayed, the instrument simultaneously acquires an optical image of the sample surface at magnifications from 1x to at least 50x (200x being feasible, depending on the sample surface). We believe that imaging the sample is extremely important as corroborative sample-identification data (the need for this capability having been illustrated by the experience of the Pathfinder rover). Very few geologists would rely on instrument data for sample identification without having seen the sample. Visual inspection provides critical recognition data such as texture, crystallinity, granularity, porosity, vesicularity, color, lustre, opacity, and so forth. These data can immediately distinguish sedimentary from igneous rocks, for example, and can thus eliminate geochemical or mineral ambiguities arising, say between arkose and granite. It would be important to know if the clay being analyzed was part of a uniform varve deposit laid down in a quiescent lake, or the matrix of a megabreccia diamictite deposited as a catastrophic impact ejecta blanket.

The unique design of the instrument (2,3), which combines Debye-Scherrer geometry with elements of standard goniometry, negates the need for sample preparation of any kind, and thus negates the need for power-hungry and mechanically-complex sampling systems that would have to chip, crush, sieve, and mount the sample for x-ray analysis. Instead, the instrument is simply rested on the sample surface of interest (like a hand lens); the device can interrogate rough rock surfaces, coarse granular material, or fine rock flour (4). A breadboard version of the instrument has been deployed from the robotic arm of the Marsokhod rover in field trials at NASA Ames, where large vesicular boulders were x-rayed to demonstrate the functionality of the instrument design, and the ability of such a device to comply with constraints imposed by a roving platform (2).

Currently under development is a flight prototype concept of this instrument that will weigh 0.3 kg, using ~4500 J of energy per sample analysis. It requires ~5 min. for XRD analysis, and about 30 min. for XRF interrogation. Its small mass and rugged design make it ideal for deployment on small rovers of the type currently envisaged for the exploration of Mars (e.g., Sojourner-scale platforms). The design utilizes a monolithic P-N junction photodiode pixel array for XRD, a Si PIN photodiode/avalanche photodiode system for XRF, and an endoscopic imaging camera system unobtrusively embedded between the detectors and the x-ray source (the endoscope with its board-mounted camera can be adapted for IR light in addition to visible wavelenths. A rugged, miniature (~7 cm3) x-ray source for the instrument has already been breadboarded (5).

(1) Marshall, J. (1996) LPS XXVII, 809, (2) Marshall, J., et al. (1996) LPS XXVII, 815, (3) Koppel, L, et al. (1995) Proc. 44th Ann. Denver Conf. Applic. X-Ray Analysis, P2-35, (4) Keaten, R., et al. (1995) EOS, Proc. AGU, F334 (P12A-19), (5) Koppel, L. & Marshall, J. (1997) Rev. Sci. Instr. (AIP), submitted.

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**X-RAY FINGERPRINTING TECHNIQUES FOR RECOGNIZING A HYDROLOGICAL ROLE IN THE FORMATION OF MINERALS ON THE SURFACE OF MARS**

METZGER, Ellen P.. Dept. of Geology, San Jose Sate University, San Jose, CA 95192-0102, metzger@geosun1.sjsu.edu and MARSHALL, John R., SETI Institute, NASA Ames Research Center, MS 239-12, Moffett Field, CA 90435, jmarshall@mail.arc.nasa.gov

Previous work has demonstrated the ability of a miniaturized XRD-XRF instrument to perform in-situ analyses without sample preparation or acquisition. Deployment of this instrument on a Martian rover will allow a large number of rapid qualitative analyses, which will maximize the diversity of samples studied and selected for possible return.

As a first step in designing a decision tree for recognizing minerals in complex mixtures, d spacings were plotted against intensity for several mineral groups comprising rock and soil types inferred for the surface of Mars (weathered basalt, playa and hydrothermal deposits, clay-rich soils). In all groups, d spacings cluster in a range from about 1-4 angstroms, which can under certain circumstances obscure patterns for individual phases. However, within the silicate family, minerals containing either bound $OH^-$ or molecules of $H_2O$ (clays, micas, amphiboles, zeolites) are characterized by a shift of peaks to higher d spacings. Large d spacings (greater than about 7 angstroms) thus act as a first-order filter for distinguishing hydrous from anhydrous silicates.

The ability to quickly verify the presence of silicates that have interacted with water has important implications for using mineral chemistry and structure to help decipher the hydrologic and atmospheric history of Mars. This represents a beginning for developing more sophisticated methods of pattern recognition. These will combine XRD and XRF analyses with optical data to rapidly discern environmentally diagnostic mineral assemblages without the necessity of identifying every peak for each individual mineral phase.

**BEHAVIOR OF WINDBLOWN SAND ON MARS: RESULTS FROM SINGLE-PARTICLE EXPERIMENTS;** J.R. Marshall [1], J. Borucki [2], and C. Sagan [3],
[1] SETI Institute/NASA Ames, MS 239-12, Moffett Field, CA 94035, [2] NASA Ames, [3] Cornell University

Experiments are investigating the behavior of individual sand grains in the high-energy martian aeolian regime. Energy partitioning during impact of a saltating grain determines grain longevity, but it also influences the way in which the bed becomes mobilized by reptation. When single grains of sand are fired into loose beds, the bed can absorb up to 90% of the impact energy by momentum transfer to other grains; it has been discovered that the impacting grains cause circular craters even at low impact angles. Hundreds of grains can be splashed by a single high-velocity (100 m/s) impact causing more bed disturbance through reptation than previously thought. The research is supported by NASA's PG&G Program.

Because the martian aeolian environment in both high energy and of long duration, the most mobile fractions of windblown sand should have eradicated themselves by attrition, unless sand supply has kept pace with destruction. It is therefore important to understand the rate of grain attrition in order to make sense of the existence of vast dune fields on Mars. Attrition has been addressed in other studies, but precise data for a single saltating grain striking a loose bed of sand have not been acquired -- the quintessential case to be understood for dunes on Mars.

To acquire these data, we are employing a compound crossbow which has the bolt-firing mechanism replaced with a pneumatically-automated sabot system. The sabot can launch <u>individual</u> grains of sand of any size between several millimeters and ~ 50 microns, at velocities up to 100m/s. This is around the maximum velocity expected for saltating grains on Mars. The sabot sled is equipped with photoelectric sensors for measuring shot velocity. Baffling of the grain's exit orifice has enabled projection of single grains without significant aerodynamic effects from the sabot. Grains are fired into loose beds of sand at about 15 degrees from the horizontal (typical saltation trajectory at impact) while being filmed on high-speed video. High-intensity pulse illumination for the grains is triggered by the solenoid-operated bow trigger. A 45 degree mirror over the impact site provides simultaneous horizontal and vertical images of the impact on each video frame. UV fluorescence is enabling grain and grain-fragment recovery.

At 100 m/s, grains of all sizes shatter into many fragments when the sand is replaced with a solid target. Kinetic energy of the grains at this velocity exceeds the critical energy for catastrophic failure of minerals. Although probably exceptional as a grain speed, it suggests that conditions on Mars might elevate materials into an attrition regime not encountered on other planets; individual grains blown across rock pavements on Mars will have short lifespans. When experimental grains impact loose (dune) sand, much, if not most of the kinetic energy is converted into momentum of other grains. Using high-speed filming, the energy involved in splashing grains at the impact site can be derived from the size of the crater, the speed of the splashed grains, and the rebound speed of the impactor. The amount of energy partitioned into material failure (as opposed to momentum) is too small a fraction of the total to be calculated under these circumstances. This does not necessarily mean that little damage occurs to the grains ( the full extent of the damage has yet to be determined) because only a small fraction of the impact energy is required for inducing brittle fracture. Damage is orders of magnitude less than during impact against solid surfaces.

In the process of video-imaging the impact of single grain into sand, it was found that impact crater were always symmetrical (no elongation in the direction of impact). This is surprising for 15 degree trajectories, and distinctly reminiscent of (but not analogous to) meteorite craters. Many hundreds of grains are injected into the air by one single high-velocity grain; the ejecta blanket covers several square centimeters even with the impact of a 100 micron particle. Every grain can trigger the entrainment of a significant portion of the bed, enough material in fact, to account for much of the grain population at the base of a saltation cloud.

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**1998 AGU Fall Meeting, San Francisco**

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# Dust on Mars: An Aeolian Threat to Human Exploration?

J. Marshall, SETI Institute, MS 239-12 NASA Ames Research Center, Moffett Field, CA 94035

The NASA HEDS Program is duly concerned for human explorers regarding the potential hazard posed by the ubiquitous dust mantle on Mars. To evaluate properties of dust that could be hazardous to humans, the MPS 2001 Lander payload will include the Mars Environmental Compatibility Assessment (MECA) experiment. This includes optical and atomic-force microscopy to evaluate soil grains for shape and size, wet chemistry to evaluate toxic substances, electrometry to evaluate triboelectric charging, and test-material palets to evaluate electrostatic and magnetic adhesion, and the hardness/abrasiveness of soil grains; these experimental subcomponents are delivered samples by the camera-equipped robotic arm of the lander which will acquire material from depths of 0.5 to 1.0 m in the soil. Data returned by MECA will be of value to both the HEDS and planetary/astrobiology communities. Dust poses a threat to human exploration because the martian system does not hydrologically or chemically remove fine particles that are being continuously generated by thermal, aeolian, and colluvial weathering, and by volcanism and impact over billions of years. The dust is extremely fine-grained, in copious quantities, ubiquitous in distribution, continually mobile, and a source of poorly-grounded static charges -- a suite of characteristics posing a particulate and electrical threat to explorers and their equipment. Dust is mobilized on global and regional scales, but probably also unpredictably and violently at local scales by dust devils. The latter might be expected in great abundance owing to near surface atmospheric instability (dust devils were detected by Pathfinder during its brief lifetime). Preliminary laboratory experiments suggest that space-suit materials subjected to windblown dust may acquire a uniform, highly adhesive dust layer that is also highly cohesive laterally owing to electrostatic forces. This layer will obscure visibility through the helmet visor, penetrate joints and fabrics, change the thermal properties of the suit, and possibly affect electronic/electrical suit functions. It is paramount that future missions address the issue of interparticle forces, and in particular, the role played by ionizing radiation in affecting these forces on Mars.

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**1998 AGU Fall Meeting, San Francisco**

# Compositional Analysis of Martian Soil: Synergism of APEX and MECA experiments on MPS 2001

R. Arvidson, Dept. of Earth and Planetary Sciences, Washington University, St Louis, MO 63130
J. Marshall, SETI Institute, MS 239-12 NASA Ames Research Center, Moffett Field, CA 94035

The APEX (ATHENA Precursor Experiment) payload for the Mars 2001 mission will analyze soil and dust with a multispectral panoramic imager and an emission spectrometer on a mast on the lander, a Moessbauer spectrometer on the lander robotic arm (RA), and APXS measurements on the Marie Curie rover. These analytical methods will provide data on elemental abundances and mineralogy. The MECA payload on the lander will apply microscopy, AFM, wet chemistry, adhesive substrates, and electrometry to determine the shape and size of particles in the soil and dust, the presence of toxic substances, and electrostatic, magnetic, and hardness qualities of particles. The two experiments will complement one another through several interactions: (1) The panoramic imager provides the geological setting in which both APEX and MECA samples are acquired, (2) The RA provides samples to MECA from the surface and subsurface and will permit APEX analytical tools access to materials below the immediate surface, (3) Comparisons can be made between elemental analyses of the Moessbauer, IR, APXS on APEX and the wet chemistry of MECA which will define trace elements (ionic species in solution) and soil redox potential and conductivity. (4) APEX bulk compositional measurements will place MECA trace measurements in context, and similarly, MECA microscopy will provide particle size data that may correlate with compositional differences determined by the APEX instruments. Additionally, lithic fragments viewed by the MECA microscope station should correlate with mineral/rock species inferred by APEX data, (5) If APEX instruments detect quartz for example, the scratch plates of the MECA microscope stage will define if a mineral of this hardness is registered during abrasion tests. This is by no means an exhaustive list of potential interactions, but it is clear that both the sheer number of analytical techniques and their complementarity should provide an analytically powerful capability for both planetary and HEDS communities.

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# X-ray Diffraction Techniques for a Field Instrument; Patterns of Lithologic Provences

J Marshall (SETI Institute/NASA Ames Research Center, MS 239-12, Moffett Field, CA 94035; 415 604 4983; e-mail John_Marshall@qmgate.arc.nasa.gov)
R Keaten (San Jose State University; 408 924 5050; e-mail rkeaten@geosun1.sjsu.edu)
(Sponsor: Rendy Keaten)

Future exploration of Mars will attempt to shed light on the mineralogy of surface materials. Instruments deployed from remote platforms should have the capability to conduct both intensive analyses as well as rapid, reconnaissance surveys while they function in the martian environment as surrogate geologists. In order to accommodate the reconnaissance mode of analysis and to compensate for analytical limitations imposed by the space-flight conditions, data analysis methods are being developed that will permit interpretation of data by recognition of signatures or "fingerprints". Specifically, we are developing a technique which will allow interpretation of diffraction patterns by recognition of characteristic signatures of different lithologic provenances. This technique allows a remote vehicle to function in a rapid-scan mode using the lithologic signature to determine where a more thorough analysis is needed.

An x-ray diffraction pattern is characterized by the angular positions of diffracted x-rays, x-ray intensity levels and background radiation levels. These elements may be used to identify a generalized x-ray signature. Lithologic signatures are being developed in two ways. A signature is composed using the ideal powder diffraction indices from the mineral assembledge common to a specific lithologic provence. This is then confirmed using a laboratory diffraction pattern of a whole rock powder. Preliminary results comparing the diffraction signatures of the major mineral assembledges common to basalt, carbonate, and evaporite basin deposits indicate that lithologies are differentiable as a "fingerprint". Statistical analyses are being performed to establish the confidence levels of this technique.

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**The Mars Environmental Compatibility Assessment (MECA) Abrasion Tool.** K. R. Kuhlman[1], M. S. Anderson[2], B. D. Hinde[2], M. H. Hecht[2], W. T. Pike[2], J. R. Marshall[3] and T. P. Meloy[4], [1]California Institute of Technology (4800 Oak Grove Drive, Jet Propulsion Laboratory Pasadena, CA 91109, kimberly.kuhlman@jpl.nasa.gov), [2]Jet Propulsion Laboratory (4800 Oak Grove Dr., Pasadena, CA 91109), [3]NASA Ames Research Center (Moffett Field, CA 94035), [4]West Virginia University (Morgantown, WV 26506)

The Mars Environmental Compatibility Assessment (MECA) experiment [1], an instrument suite to be flown on Mars Surveyor 2001, will include a tool for doing simple mineralogical scratch and streak tests on particles from the Martian regolith. The Abrasion Tool will be applied to particles that adhere themselves to highly polished substrates of various hardnesses. Granular soil components will be subjected to a compressive force of about 3 N using a leaf spring. The spring will be applied with a paraffin actuator capable of a 0.76 mm throw to achieve a maximum displacement of about 7.5 mm at the tip of the tool. The pressure per grain will be dependent on the grain size, the number of grains that adhere to the substrate and the number of grains in compression. The pressure per particle is expected to be on the order of 100 MPa - 1 GPa. The MECA sample wheel containing the substrates will be rotated after the particles are placed in compression to produce scratches or pits.

A primary goal of the Abrasion Tool is to identify quartz (Mohs' hardness = 7) using substrates of varying hardnesses. Quartz is considered hazardous to future human explorers of Mars because it can cause silicosis of the lungs if it is of respirable size. It is also hazardous to machinery, structures, and space suits because of its ability to abrade and scratch surfaces. Since large quantities of minerals harder than quartz are not expected, any scratches produced on polished quartz substrates might be reasonably attributed to quartz particles (Figure 1), although there may be minerals such as impact metamorphic diamond in the soils. Careful calibration of the tool will be necessary to ensure that grains are not overloaded; for example, a steel ball pressed into glass will produce a Hertzian fracture, even though it is softer than glass. Other minerals, such as magnetite (Mohs' hardness = 6.5) have been shown to scratch glass ceramics such as Zerodur (Mohs' hardness = 6.5) (Figure 2). Thus, minerals can be differentiated: note that regardless of the mineral species, if any particle is harder than 6.5 it will certainly be an interesting discovery for both planetary geology and human exploration concerns.

The scratches will be identified using the 6X optical microscope and profiled with the atomic force microscope included in the MECA instrument suite. Analysis of the scratch morphology will yield evidence concerning the shape of the particle responsible for producing each scratch. For example, angular grains should leave vertical cracks with microconchoidal lateral chipping [2], while rounded grains might leave chattermarks, or nested partial Hertzian cracks [3]. Particle shape can thus be inferred from these indentation modes, as well as material hardness. In addition, particle size information may also be available if pits caused by rolling particles can be identified. Converse to scratching, the minerals may be crushed at their contact points, and be smeared onto the target substrates to leave what geologists refer to as "streaks". These are cold-welded trails of mineral material that have structure and color indicative of mineral composition. The AFM will determine the morphology of these streaks, while the microscope will ascertain the color. On the harder substrates, we might expect streaking to dominate; on the softer substrates, scratching may dominate. Progressions of material interactions across the substrate selection will be a valuable source of data for mineral discrimination. It should also be noted that many minerals have coatings (such as iron oxides), and these will have to be differentiated from the host mineral grains; laboratory tests will establish the effects of such coatings on the scratch results. Finally, we note that the microscope will provide corroborative data regarding likely mineral species by grain shapes, fracture patterns, surface textures, color, and UV fluorescence reactions.

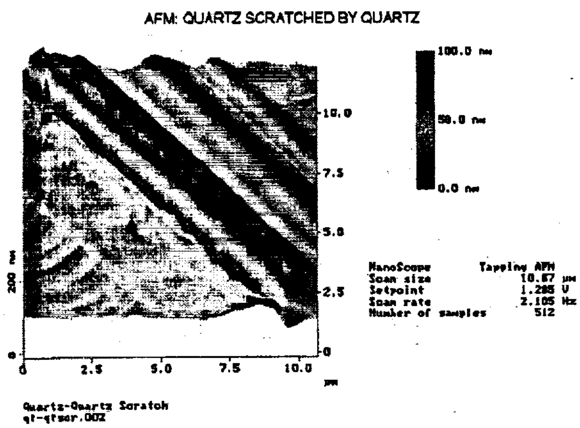


Figure 1. Atomic force microscope image of a scratch on a flat quartz surface produced by an angular quartz fragment.

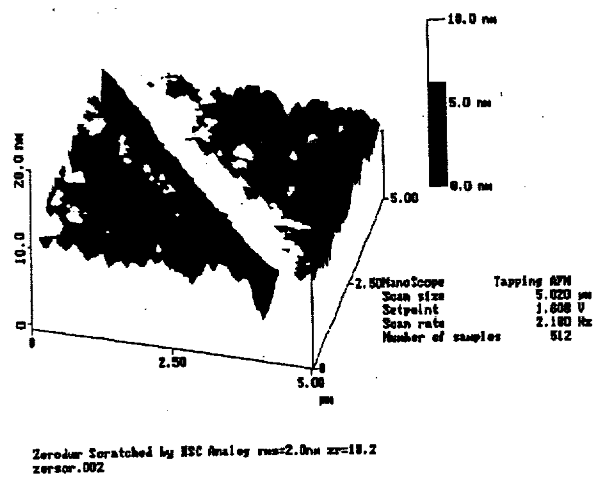


Figure 2. Atomic force microscope image of a scratch produced by abrading highly polished Zerodur (glass ceramic) with the standard JSC Martian soil simulant, JSC Mars-1 [4]. The scratch is attributed to magnetite which is a relatively large fraction of the simulant.

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**References:** [1] http://mars.jpl.nasa.g ... *ic Home Page,*
[2] Lawn, B., et al. (1993) *Fracture of* ... Cambridge),
[3] Marshal J. R., et al. (1987) *Clastic* ... [4] Allen, C.
C., et al. (1998) *LPSC XXIX.*

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**Fifth International Conference on Mars, July 18-23, 1999 Pasadena, CA**

# MECA Electrometer: Initial Experimental Results

M. Buehler, L-J. Cheng, & O. Orient, Jet Propulsion Laboratory, Cal Tech
R. Gompf, J. Bayliss, and J. Rauwerdink, NASA Kennedy Space Flight Center
J. Marshall, SETI Institute/NASA Ames Research Center

**Introduction**: The Mars '01 lander contains an electrometer designed to evaluate the electrostatic nature of the Martian regolith (soil) and atmosphere. The electrometer is part of MECA (Mars Environmental Compatibility Assessment) project. The objective is to gain a better understanding of the hazards related to the human exploration of Mars The sensor has an electric field sensitivity of 35 kV/cm·V and room temperature drift of ~3 μV/sec. The sensor has been operated as low as –60°C where the drift is undetected.

**Electrometer**: As seen in Fig. 1, the instrument has four sensor types: (a) triboelectric field, (b) electric-field, (c) ion current, (d) temperature. The triboelectric field sensor array contains five insulating materials to determine material charging effects as the scoop is dragged through the Martian regolith.

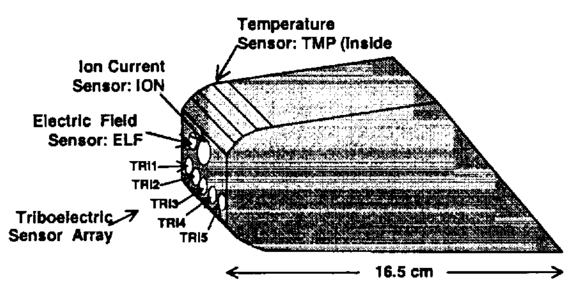


Figure 1. Electrometer sensor suite mounted in the heel of the Mars '01 scoop. The electrometer operates over an 8-wire serial interface, is housed in a volume of ~50 cm$^3$, consumes less than 250 mW, and weighs ~50 g.

In operation, the scoop will be rubbed against the Martian soil as depicted in Fig. 2. Then at the end of the rubbing period, the scoop will be raised and the response of the triboelectric sensors measured. Recommended operational parameters are: D1 = 10 cm is the traverse distance, D2 = 1 cm is the liftoff distance, D3 = 0.5 to 1 cm is the penetration depth, t1 = 10 s is the traverse time, t2 = 0.5 s is the liftoff time, t3 = 1 s is the switch close time, t4 = 19 s is the data acquisition time, and t5 = 0.1 s is the time between data points.

Of concern is dust cling to the sensors after lift off. The dust will reduce the triboelectric response. Various particle removal techniques will be explored.

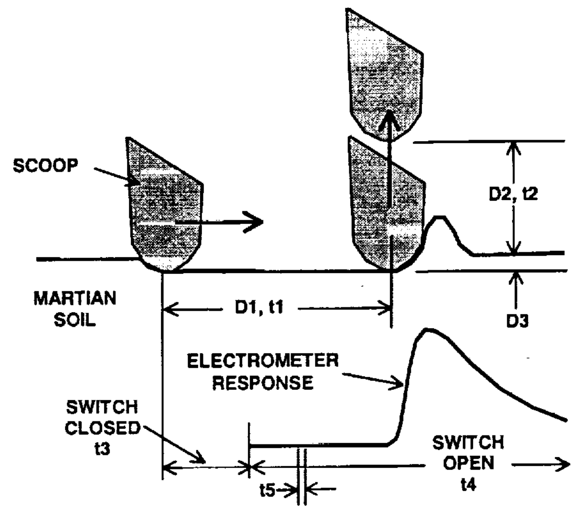


Figure 2. Operational scenario for the scoop

**Experimental Results**: In order to test out the viability of the apparatus, preliminary experiments involved the rubbing of sensors on wool. The results from prototype 7, ELE7, are shown in Fig. 2. The prototype was mounted on an automatic rubbing apparatus and the five triboelectric sensors were rubbed on wool. The results show that Teflon has the largest negative response which is expected from the Triboelectric series [1]. The response also shows the slow leak of the charge from the sensors.

Note that the sensor, TRI3, which was covered with a sheet of the antistatic material, Velostat, did not responsed. This is because the current data acquisition rate of one sample every 1.5 seconds is too slow to capture the fast transient from Velostat. The rate needs to be one sample every 0.1 second.

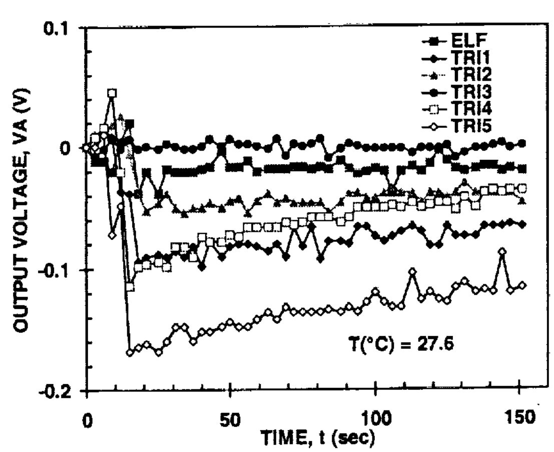


Figure 3. Rubbing experiment where triboelectric sensors were rubbed with wool felt. TRI1 is ABS, TRI2 is polycarbonate, TRI3 is Velostat, TRI4 is Rulon-J, and TRI5 is Teflon.

The results in Fig 4 show the response for two, millimeter-size basalt particles placed on TRI3. After a baseline period lasting 30 sec, the first particle was blown off the sensor using a nitrogen gas jet where upon the first downward response was measured. At the moment the particle was removed from TRI3 it landed on ELF which had a positive response. The second particle was removed after 50 sec and the second downward shift was measured.

**Discussion**: Further experimentation is planned in Mars simulators where the atmosphere will be $CO_2$ at 5 mb and the temperature will be controlled to between –60 and 20°C. The soils planned are hematite, basalt, and quartz.

**Conclusions**: Preliminary results from the electrometer are encouraging. They show that rubbing with wool produces a strong (in the 0.1 V range) response using an automated rubbing apparatus. In addition, the charge on a single basalt particle was easily detected.This suggests that this apparatus can be used in particle cleaning experiments where the removal of charged particles is detected by an abrupt change in the electrometer response.

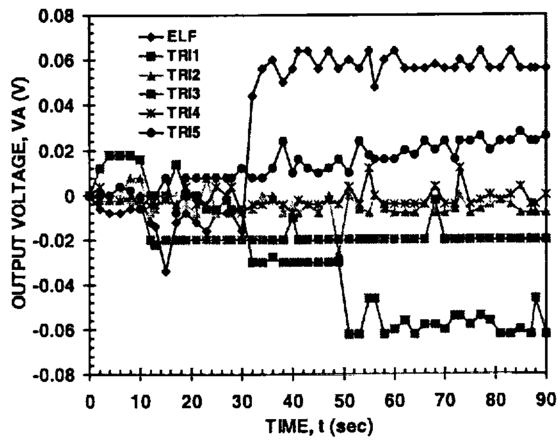


Figure 4. Room ambient particle removal experiment using TRI3. TRI1 is ABS, TRI2 is polycarbonate, TRI3 is Teflon, TRI4 is Rulon-J, and TRI5 is Teflon.


**References**: 1. A. Cross, "Electrostatics: Principles, Problems and Applications", Adam Hilger (Bristol, UK)



**Acknowledgments**: The work described in this paper was performed by the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration. The authors are indebted to the managers who have encouraged this work. In particular from JPL, Michael Hecht, Lynne Cooper, and Joel Rademacher, from WVU, Tom Meloy, and from KSC Haesoo Kim and Rupert Lee.

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**Fifth International Conference on Mars, July 18-23, 1999 Pasadena, CA**

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The Mars Environmental Compatibility Assessment MECA Abrasion Tool

K. R.. Kuhlman1 M. S. Anderson2 B. D. Hinde2, M. H. Hecht2, W. T. Pike2 J. Marshall3 T. P. Meloy4 and T. Cobbly4

1. California Institute of Technology (4800 Oak Grove Drive, Jet Propulsion Laboratory Pasadena, CA 91109, kimberly.kuhlman@jpl.nasa.gov, 2.Jet Propulsion Laboratory ,4800 Oak Grove Dr., Pasadena, CA 91109),3. NASA Ames Research Center (Moffett Field, CA 94035), 4. West Virginia University (Morgantown, WV 26506)

The Mars Environmenal Compatibility Assessment (MECA) experiment, an instrument suite to be flown on Mars Surveyor 2001, will include a tool for doing simple mineralogical scratch and streak tests on particles from the Martian regolith. The Abrasion Tool will be applied to particles that adhere to highly polished substrates of various hardnesses. Granular soil components will be subjected to a compressive force of about 3 N using a leaf spring. The spring will be applied with a paraffin actuator capable of a 0.76 mm throw to achieve a maximum displacement of about 7.5 mm at the tip of the tool. The pressure per grain will be dependent on the grain size, the number of grains that adhere to the substrate and the number of grains in compression. The pressure per particle is expected to be on the order of 100 MPa - 1 GPa. The MECA sample wheel containing the substrates will be rotated after the particles are placed in compression to produce scratches or pits.

A primary goal of the Abrasion Tool is to identify quartz (Mohs' hardness = 7) using substrates of varying hardnesses. Quartz is considered hazardous to future human explorers of Mars because it can cause silicosis of the lungs if it is of respirable size. It is also hazardous to machinery, structures, and space suits because of its ability to abrade and scratch surfaces. Since large quantities of minerals harder than quartz are not expected, any scratches produced on polished quartz substrates might be reasonably attributed to quartz particles (Figure 1), although there may be minerals such as impact metamorphic diamond in the soils. Careful calibration of the tool will be necessary to ensure that grains are not overloaded; for example, a steel ball pressed into glass will produce a Hertzian fracture, even though it is softer than glass. Other minerals, such as magnetite (Mohs' hardness = 6.5) have been shown to scratch glass ceramics such as Zerodur (Mohs' hardness = 6.5) (Figure 2). Thus, minerals can be differentiated: note that regardless of the mineral species, if it is harder than 6.5 it will certainly be an interesting discovery for both planetary geology and human exploration concerns.

The scratches will be identified using the 6X optical microscope and profiled with the atomic force microscope included in the MECA instrument suite. Analysis of the scratch morphology will yield evidence concerning the shape of the particle responsible for producing each scratch. For example, angular grains should leave vertical cracks with microconchoidal lateral chipping [21], while rounded grains might leave chattermarks, or nested partial Hertzian cracks [2]. Particle shape can thus be inferred from these indentation modes, as well as material hardness. In addition, particle size information may also be available if pits caused by rolling particles can be identified. Converse to scratching, the minerals may be crushed at their contact points, and be smeared onto the target substrates to leave what geologists refer to as "streaks". These are cold-welded trails of mineral material that have structure and color indicative of mineral composition.

The AFM will determine the morphology of these streaks, while the microscope will ascertain the color. On the harder substrates, we might expect streaking to dominate; on the softer substrates, scratching may dominate. Progressions of material interactions across the substrate selection will be a valuable source of data for mineral discrimination. It should also be noted that many minerals have coatings (such as iron oxides), and these will have to be differentiated from the host mineral grains; laboratory tests will establish the effects of such coatings on the scratch results. Finally, we note that the microscope will provide corroborative data regarding likely mineral species by grain shapes, fracture patterns, surface textures, color, and UV fluorescence reactions.

References: [1]Lawn, B.(1993) Fracture of Brittle Solids Cambridge University Press, [2] Marshall J. R.(ed.) Clastic Particles (1987), Van Nostrand Reinhold.

Figure 1. Atomic force microscope image of scratch produced by JSC Mars-1 on highly polished Zerodur (glass ceramic). The scratch is attributed to the large fraction of magnetite in the simulant.

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**AEOLIAN SAND TRANSPORT IN THE PLANETARY CONTEXT: RESPECTIVE ROLES OF AERODYNAMIC AND BED-DILATANCY THRESHOLDS.** J.R. Marshall[1], J. Borucki[2], and C. Bratton[1], [1]SETI Institute, NASA Ames Research Center, MS 239-12, Moffett Field, CA 94035-1000, [2]NASA Ames Research Center.

The traditional view of aeolian sand transport generally estimates flux from the perspective of aerodynamic forces creating the airborne grain population, although it has been recognized (1) that "reptation" causes a significant part of the total airborne flux; reptation involves both ballistic injection of grains into the air stream by the impact of saltating grains as well as the "nudging" of surface grains into a creeping motion. Whilst aerodynamic forces may initiate sand motion, it is proposed here that within a fully-matured grain cloud, flux is actually governed by two thresholds: an aerodynamic threshold, and a bed-dilatancy threshold. It is the latter which controls the reptation population, and its significance increases proportionally with transport energy. Because we only have experience with terrestrial sand transport, extrapolations of aeolian theory to Mars and Venus have adjusted only the aerodynamic factor, taking gravitational forces and atmospheric density as the prime variables in the aerodynamic equations, but neglecting reptation.

The basis for our perspective on the importance of reptation and bed dilatancy is a set of experiments that were designed to simulate sand transport across the surface of a martian dune. Using a modified sporting crossbow in which a sand-impelling sabot replaced the bolt-firing mechanism, individual grains of sand were fired at loose sand targets with glancing angles typical of saltation impact; grains were projected at ~80 m/s to simulate velocities commensurate with those predicted for extreme martian aeolian conditions (2). The sabot impelling method permitted study of individual impacts without the masking effect of bed mobilization encountered in wind-tunnel studies. At these martian impact velocities, grains produced small craters formed by the ejection of several hundred grains from the bed. Unexpectedly, the craters were not elongated, despite glancing impact; the craters were very close to circular in planform. High-speed photography showed them to grow in both diameter and depth after the impactor had ricochetted from the crater site. The delayed response of the bed was "explosive" in nature, and created a miniature ejecta curtain spreading upward and outward for many centimeters for impact of 100-300 micron-diameter grains into similar material. Elastic energy deposited in the bed by the impacting grain creates a subsurface stress regime or "quasi-Boussinesq" compression field (Figure 1). Elastic recovery of the bed occurs by dilatancy; shear stresses suddenly convert the grains from closed to open packing, and grains are consequently able to eject themselves forcefully from the impact site. Random jostling of the grains causes radial homogenization of stress vectors and a resulting circular crater. There is a great temptation to draw parallels with cratering produced by meteorite impacts, but a rigorous search for common modelling ground between the two phenomena has not been conducted at this time.

For every impact of an aerodynamically energized grain, there are several hundred grains ejected into the wind for the high-energy transport that might occur on Mars. Many of these grains will themselves become subject to the boundary layer's aerodynamic lift forces (their motion will not immediately die and add to the creep population), and these grains will become indistinguishable from those lifted entirely by aerodynamic forces. As each grain impacts the bed, it will eject even more grains into the flow. A cascading effect will take place, but because it must be finite in its growth, damping will occur as the number of grains set in motion causes mid-air collisions that prevent much of the impact energy from reaching the surface of the bed -- thus creating a dynamic equilibrium in a high-density saltation cloud.

It is apparent from Figure 1 that for a given impact energy, the stress field permits a smaller volume of grains to convert to open packing as the size of the bed grains increases, or as the energy of the "percussive" grain decreases (by decrease in velocity or mass). Thus, the mass of the "repercussive" grain population that is ejected from the impact site becomes a function of the scale of the stress field in relation to the scale of the bed material (self-similarity being applicable if both bed size and energy are simultaneously adjusted). In other words, in a very high energy aeolian system where an aerodynamically raised grain can ballistically raise many more grains, the amount of material lifted into the wind becomes largely a function of a dilatancy threshold. If this threshold is exceeded, grains are repercussively injected into the saltation cloud. The "dilatancy threshold" may be defined in terms of the saltation percussive force required to convert the bed, through elastic response, from a closed to an open packing system. If open packing cannot be created, the grains cannot escape from the impact site, even though the elastic deformation and percussive force may be able to reorganize the grains with respect to one another. As the crossbow experiments showed, for an ever-increasing bed grain size, a point is reached when no material can be moved because the energy of the percussive grain is insufficient to dilate the relatively coarse bed. Although this seems to be stating the obvious -- that too little energy will not cause the bed to splash -- the consequences of exceeding the "splash threshold" by dilatancy are not so obvious for high-energy aeolian transport. It is noted that the force required to elastically dilate the bed has to overcome Coulombic grain attractions such as dipole-dipole coupling, dielectric, monopole, contact-induced dipole attractions, van der Waals forces, molecular monolayer capillary forces, as well as the mechanical interlocking frictional resistance of the grains.

On Mars, it is predicted that the dilatancy threshold may be the prime control of grain flux. On earth, the aerodynamic thresholds and dilatancy thresholds are of about equal importance (1). On Venus, the aerodynamic threshold dominates (Figure 2). Thus, aeolian transport of sand in the planetary context should be viewed as a variable combination of primarily these two thresholds, not simple a function of an aerodynamic threshold adjusted for gravity and atmospheric density.

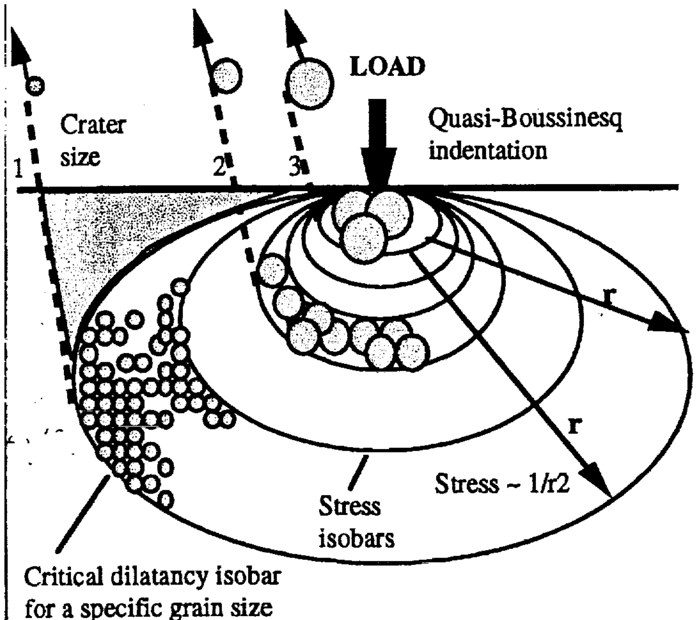


**Figure 1: Relationship of stress field magnitude to dilatable bed volume**

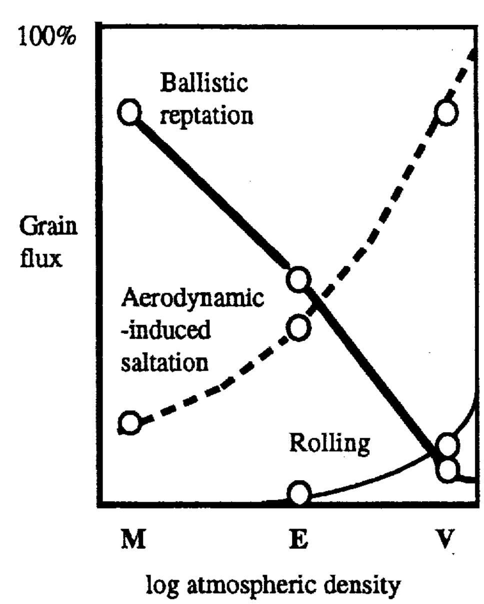


**Figure 2: Relative roles of flux modes for Mars, Earth, & Venus**

This work was supported by the NASA PG & G Program.

(1) Anderson R.S. (1987) Document BB-56, Univ. Washington. (2) Sagan C. (1973) JGR 78, 4155.

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# UNIQUE AEOLIAN TRANSPORT MECHANISMS ON MARS: RESPECTIVE ROLES OF PERCUSSIVE AND REPERCUSSIVE GRAIN POPULATIONS IN THE SEDIMENT LOAD

MARSHALL, John R., SETI Institute, MS 239-12, NASA Ames Research Center, Moffett Field, CA 94035-1000, jmarshall@mail.arc.nasa.gov

Experiments show that when sand-size grains impact a sediment surface with energy levels commensurate for Mars, small craters are formed by the ejection of several hundred grains from the bed. The experiments were conducted with a modified crossbow in which a sand-impelling sabot replaced the bolt-firing mechanism. Individual grains of sand could be fired at loose sand targets to observe ballistic effects unhindered by aerodynamic mobilization of the bed. Impact trajectories simulated the saltation process on dune surfaces.

Impact craters were not elongated despite glancing (15 deg.) bed impact; the craters were very close to being circular. High-speed photography showed them to grow in both diameter and depth after the impactor had ricochetted from the crater site. The delayed response of the bed was "explosive" in nature, and created a miniature ejecta curtain spreading upward and outward for many centimeters for impact of 100-300 um-diameter grains into similar material. This behavior is explained by deposition of elastic energy in the bed by the "percussive" grain. Impact creates a subsurface stress regime or "quasi-Boussinesq" compression field. Elastic recovery of the bed occurs by dilatancy; shear stresses suddenly convert the grains to open packing and they consequently become forcefully ejected from the site. Random jostling of the grains causes radial homogenization of stress vectors and a resulting circular crater. A stress model based on repercussive bed dilatancy and interparticle adhesive forces (for smaller grains) predicts, to first order, the observed crater volumes for various impact conditions.

On earth, only a few grains are mobilized by a percussive saltating grain; some grains are "knudged" along the ground, and some are partly expelled on short trajectories. These motions constitute reptation transport. On Mars, saltation and reptation become indistinct: secondary or "repercussive" trajectories have sufficient vertical impulse to create a dense saltation population of many tens or hundreds of grains for each single high-speed saltation percussion of the bed. Impact cascading will lead to near-surface distortion of the boundary layer, and choaked flow formed by a dense "slurry" of sand, with the majority of grains mobilized by repercussive forces rather than by aerodynamic lift. This proceeds until a fully-matured transport layer imposes self-limitations as grain-population density constrains the free-path motion of individial grains.

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# BEHAVIOR OF WINDBLOWN SAND ON MARS: RESULTS FROM SINGLE-PARTICLE EXPERIMENTS

J.R. Marshall [1] , J. Borucki [2] , and C. Sagan [3] , [1] SETI Institute/NASA Ames, MS 239-12, Moffett Field, CA 94035, [2] NASA Ames, [3] Cornell University

Experiments are investigating the behavior of individual sand grains in the high-energy martian aeolian regime. Energy partitioning during impact of a saltating grain determines grain longevity, but it also influences the way in which the bed becomes mobilized by reptation. When single grains of sand are fired into loose beds, the bed can absorb up to 90% of the impact energy by momentum transfer to other grains; it has been discovered that the impacting grains cause circular craters even at low impact angles. Hundreds of grains can be splashed by a single high-velocity (100 m/s) impact causing more bed disturbance through reptation than previously thought. The research is supported by NASA's PG&G Program.

Because the martian aeolian environment in both high energy and of long duration, the most mobile fractions of windblown sand should have eradicated themselves by attrition, unless sand supply has kept pace with destruction. It is therefore important to understand the rate of grain attrition in order to make sense of the existence of vast dune fields on Mars. Attrition has been addressed in other studies, but precise data for a single saltating grain striking a loose bed of sand have not been acquired -- the quintessential case to be understood for dunes on Mars.

To acquire these data, we are employing a compound crossbow which has the bolt-firing mechanism replaced with a pneumatically-automated sabot system. The sabot can launch individual grains of sand of any size between several millimeters and ~ 50 microns, at velocities up to 100m/s. This is around the maximum velocity expected for saltating grains on Mars. The sabot sled is equipped with photoelectric sensors for measuring shot velocity. Baffling of the grain's exit orifice has enabled projection of single grains without significant aerodynamic effects from the sabot. Grains are fired into loose beds of sand at about 15 degrees from the horizontal (typical saltation trajectory at impact) while being filmed on high-speed video. High-intensity pulse illumination for the grains is triggered by the solenoid-operated bow trigger. A 45 degree mirror over the impact site provides simultaneous horizontal and vertical images of the impact on each video frame. UV fluorescence is enabling grain and grain-fragment recovery.

At 100 m/s, grains of all sizes shatter into many fragments when the sand is replaced with a solid target. Kinetic energy of the grains at this velocity exceeds the critical energy for catastrophic failure of minerals. Although probably exceptional as a grain speed, it suggests that conditions on Mars might elevate materials into an attrition regime not encountered on other planets; individual grains blown across rock pavements on Mars will have short lifespans. When experimental grains impact loose (dune) sand, much, if not most of the kinetic energy is converted into momentum of other grains. Using high-speed filming, the energy involved in splashing grains at the impact site can be derived from the size of the crater, the speed of the splashed grains, and the rebound speed of the impactor. The amount of energy partitioned into material failure (as opposed to momentum) is too small a fraction of the total to be calculated under these circumstances. This does not necessarily mean that little damage occurs to the grains ( the full extent of the damage has yet to be determined) because only a small fraction of the impact energy is required for inducing brittle fracture. Damage is orders of magnitude less than during impact against solid surfaces.

In the process of video-imaging the impact of single grain into sand, it was found that impact crater were always symmetrical (no elongation in the direction of impact). This is surprising for 15 degree trajectories, and distinctly reminiscent of (but not analogous to) meteorite craters. Many hundreds of grains are injected into the air by one single high-velocity grain; the ejecta blanket covers several square centimeters even with the impact of a 100 micron particle. Every grain can trigger the entrainment of a significant portion of the bed, enough material in fact, to account for much of the grain population at the base of a saltation cloud.

 

# "ELECTROSTRUCTURAL PHASE CHANGES" IN CHARGED PARTICULATE CLOUDS: PLANETARY AND ASTROPHYSICAL IMPLICATIONS.

J.R. Marshall, SETI Institute, NASA Ames Research Center, MS 239-12, Moffett Field, CA 94035-1000

There is empirical evidence that freely-suspended triboelectrostatically charged particulate clouds of dielectric materials undergo rapid conversion from (nominally) monodispersed "aerosols" to a system of well-defined grain aggregates after grain motion or fluid turbulence ceases within the cloud. In United States Microgravity Laboratory Space Shuttle experiments USML-1 and USML-2, (1,2) it was found that ballistically-energized grain dispersions would rapidly convert into populations of filamentary aggregates after natural fluid (air) damping of grain motion. Unless continuously disrupted mechanically, it was impossible to maintain a non-aggregated state for the grain clouds of sand-size materials. Similarly, ground-based experiments (3) with very fine dust-size material produced the same results: rapid, impulsive "collapse" of the dispersed grains into well-defined filamentary structures. In both ground-based and microgravity experiments, the chains or filaments were created by long-range dipole electrostatic forces and dipole-induced dielectric interactions (1), not by monopole interactions. Maintenance of the structures was assisted by short-range static boundary adhesion forces and van der Waals interactions. When the aggregate containers in the USML experiments were disturbed after aggregate formation, the quiescently disposed filaments would rearrange themselves into fractal bundles and tighter clusters as a result of enforced encounters with one another.

The long-range dipole interactions that bring the grains together into aggregates are a product of randomly-distributed monopole charges on the grain surfaces. In computer simulations, it has been shown (1) that when the force vectors of all the random charges (of both sign) on a grain are resolved mathematically by assuming Coulombic interaction between them, the net result is a dipole moment on individual grains, even though the grains are electrically neutral insofar as there is no predominance, on their surface, of one charge sign over another. The random charges of both sign derive from natural grain-to-grain interactions that produce triboelectrification via charge exchange every time grain surfaces make contact with one another.

The conversion from a random distribution of grains (upon which there are randomly distributed charges) into an organization of electrostatically-ordered aggregates, can be regarded (within the framework of granular-material science) as an "electrical or Coulombic phase change" of the particulate cloud. It is not totally dissimilar from the more normal phase-change concept in which, for example, a gas with long free-path-molecules suddenly becomes a solid as a result of structural ordering of the molecules (notably, also the result of electronic forces, albeit at a different scale). In both the gas-to-solid case, and the aerosol-to-aggregate case, the same materials and charges are present before and after the phase change, but their arrangement now has a higher degree of order and a lower-energy configuration. An input of energy into the system is required to reverse the situation. The aggregates in the USML experiments were observed to undergo at least two phase changes as noted above.

The point about phase changes, and by implication, the "electrostructural" reorganizations in particulate clouds, is the following:

(a) they can occur very rapidly, almost spontaneously, above a critical cloud density,

(b) in going from a higher energy state to a lower energy state, they convert to a denser system, (c) energy must be required to reverse the situation, implying that energy is released during the high-to-low energy phase change.

In applying this information to natural particulate clouds, some inferences can be made (it is stressed that reference is still to dielectric materials attracted by dipole forces). There are several natural settings to which the USML observations apply, and to which the phase-change implications likewise apply. Dense clouds of triboelectrically-charged, kinetically-energized grains are to be found in volcanic eruptions (particularly on earth), aeolian dust storms (particularly on Mars), meteorite impact ejecta curtains (on all planets), in "immature" debris rings around planets (e.g., that from which our own Moon may have condensed), and in gravitationally collapsing protoplanetary dust/planetesimal debris disks where dielectric granules are being increasingly brought into collisional relationships with one another (increasing both charge exchange and physical proximity). It is noted that in many of these cases, the degree of electrical charging on the grains is likely to be much higher than that in the USML experiments where charging was not enhanced above the "normal", naturally encountered level for the particular materials (quartz, glass, and various silicate minerals).

Application of the phase-change concept suggests that volcanic, aeolian, and impact debris clouds may, under certain circumstances, undergo rapid, impulsive, or even catastrophic collapse into a denser state that will lead to rapid precipitation or fall-out of suspended particulates. Although this idea has been suggested previously by the author (1,2), the phase-change concept possibly permits some new insights into cloud-system behavior. For example, in a protoplanetary debris disk, the work of gravity may suddenly be enhanced by electrostatically-driven collapse of the system when materials reach a critical intergranular spacing or grain number density. This might reduce the rate of planet formation by orders of magnitude (considering the ratio of g-forces to electrostatic ones for very small grains in close proximity), and indeed, it might drive the collapse into a system configuration that would perhaps not be created by gravity alone.

In any system undergoing electrostructural phase changes, there becomes less electrostatic energy available for driving the motion of materials. And an increasing amount of mechanical, thermal, and other forms of energy must be exerted to change the Coulombic phase of the cloud, because the electrostatic forces increasingly bind the particulates into less malleable, more resistant states. At this time, no investigation has been made of the implication of energy release during electrostructural phase changes, but it can be speculated that the statically-driven collisions must ultimately lead to an increase of thermal energy of the particulate system. In a large system such as a protoplanetary disk, the amount of heat suddenly released during an impulsive change of state, may drive chemical reactions and thermal fusion of dense grain systems. There are related issues of internal cloud friction and "apparent viscosity" of cloud motion associated with phase changes, as discussed in a companion abstract (4).

In some cloud systems, the electrostatic state of individual grains may be dominated by monopoles or net charge. This can occur in some volcanic eruption plumes, and may well occur in a protoplanetary disk where a newly-born star generates clouds of positively-charged particulates as a result of electron stripping by cosmic-ray bombardment. Grains of like charge will repel one another and resist the phase changes discussed so far. However, as the cloud increases its density, most of the grains will become shielded from the solar rays, and the electron clouds released from the ionized grain surfaces may return to some electronic state that enables the grains to participate in the aggregation process. Since it is the part of the cloud closest to the star that has the most ionized grain surfaces, this inner zone should be the most resistance to collapse.

In conclusion, the concept of "electrostructural phase changes" in dense granular systems may be a useful exploratory framework for envisaging and modeling cloud behavior. This work was supported by the NASA Exobiology Program.

(1) Marshall J.R. (1997) USML-2/USMP-3 L+1 Report, NASA CP, In press. (2) Marshall J.R. (1994) NASA CP 3272, 717-732. (3) Marshall J.R. et al. (1981) NASA TM 84211, 208. (4) Marshall J.R., This volume.

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# DIAGNOSTIC CLAST-TEXTURE CRITERIA FOR RECOGNITION OF IMPACT DEPOSITS.

J.R. Marshall[1], C. Bratton[1], K.O. Pope[2], and A.C. Ocampo[3], [1]SETI Institute/NASA Ames Research Center, MS 239-12, Moffett Field, CA 94035-1000, [2]Geo.Eco.Arc. Research, [3]Jet Propulsion Laboratory.

It is difficult to find definitive evidence for impact in the geological record because there are many endogenous geological processes that can produce diamictites similar to those generated by impact ejecta (1). The classic impact criteria of shock fabrics in certain minerals, and iridium layers, for example, may be either difficult to find, or long-since erased from the impact site (shock fabrics also anneal with time). It is important to be able to recognize impact-generated materials in order to understand earth's crustal development and biological evolution. In future exploration of Mars and other solar-system bodies, recognition of impact materials will be important for elucidating planetary evolution, planetary volatile inventories, and exobiological issues.

The cobble depicted in Figure 1 is typical of many that have been found in diamictite deposits in Belize generated by the Chicxulub K-T impact event (2). The pebbles are roughly-hewn in general shape with smoothed corners and edges. Surfaces are almost uniformly frosted (on both protuberances and hollows), but some asperities are glazed. Optical microscopy and thin-section petrographic microscopy reveal the frosting to be only a few microns thick, with a well-defined granular structure; grains are the same size as those composing the bulk of the limestone, but their clearer appearance may represent annealing. One or two adjacent pebble faces are often decorated

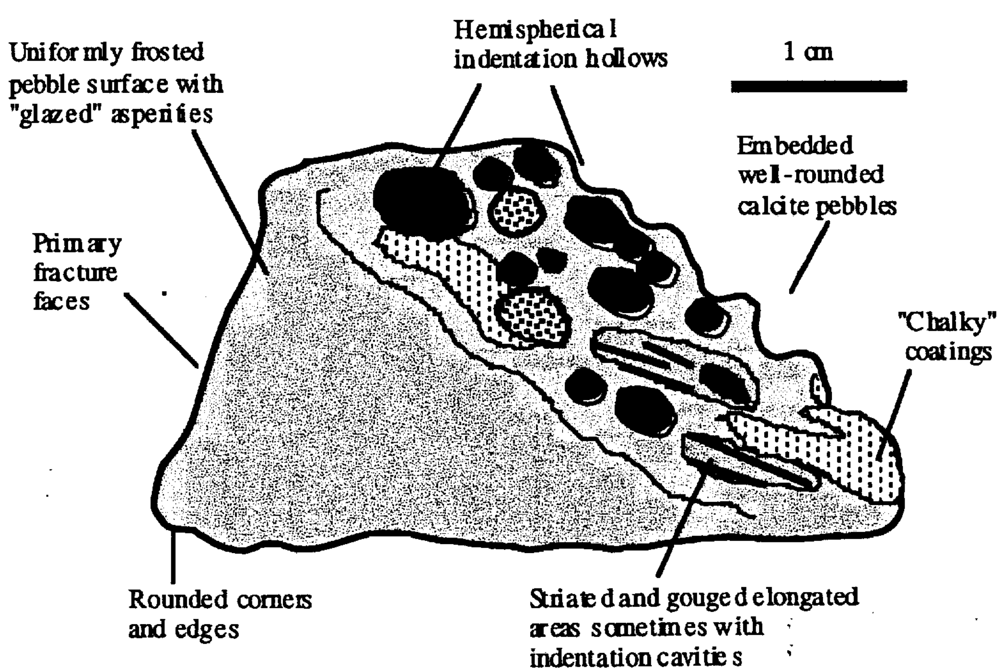


**Figure 1: Limestone cobble from Chicxulub ejecta**

with striated gouges, and closely-spaced hemispherical depressions representing indentation hollows produced by well-rounded impacting clasts of up to 0.5 cm diam. Some of the impactors are still embedded in the cobble surface. Non-destructive x-ray diffraction techniques (3) showed the impactors to be of the same mineralogy as the target cobble. We believe the unusual glazing and frosting to be related to the impact event, but this must be reconciled with its survival for over 60 my, since it is composed of one of the most easily alterable of substances, $CaCO_3$.

We focus, however, on the non-fractured rounded pebbles that appear to have impacted the larger cobble as a swarm of clasts, probably encountered during ballistic flight. It cannot be defined whether the cobble swept through the pebble cloud, or the pebbles rained upon a slower-moving cobble. Two interesting questions arise: (1) Where did large numbers of such well-rounded pebbles come from in the ejecta curtain?, and (2) How did they embed themselves in a nominally brittle rock without suffering damage? Are the well-rounded pebbles crystalline (devitrified) melt spherules? Further investigations are in progress. Figure 2 addresses the embedding problem. If the cobble was cold and brittle, impact of well-rounded pebbles would have produced Hertzian fracture patterns (a) in the virtually elastically isotropic cobble target. For penetration depths of ~0.5 of the impactor diameter, the pebbles would require a relative impact velocity sufficient to cause pebble fragmentation and crushing, and the development of a complex Hertzian-Boussinesq fracture field (b) involving deep fracturing and lateral surface spalling (impact velocities > 50 m/s). The existing relationship could only evolve by the impact of cold, hard pebbles into a soft, plastic cobble surface (c). For limestone to have been plastic, it must have been at elevated temperature, but to prevent calcification of the material, the ambient pressure must also have been elevated. This would be possible either in the impact's gas plume, or within the confines of a thin aerodynamically-produced shock bow generated by supersonic ballistic motion of the cobble. In the latter case, it is implied that the cobble swept through the pebbles rather than vice-versa. Although there are high T-P conditions associated with volcanism, such textures have not been reported on volcaniclastic materials, nor from other high T-P environments; e.g., metamorphic (as far as the authors are aware). We propose that this very easily recognizable embedding and indentation surface texture can be used as a diagnostic criterion for the recognition of impact ejecta. The term "peening texture" is suggested, because it is absolutely analogous to the plastic-deformation induced, metal-surface textures generated by ball-bearing bombardment used in engineering metallurgy to work-harden metal surfaces.

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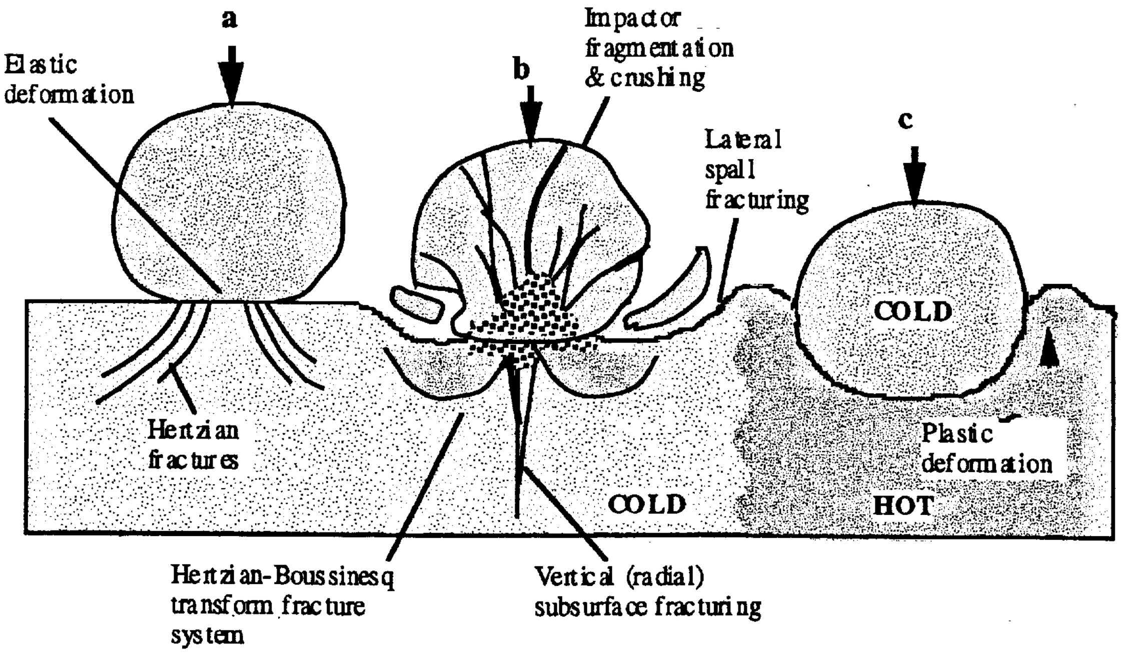


**Figure 2: Impact Responses as a Function of KE and T**

(1) Marshall J.R. (1993) Ann. Meet. Pacific Div. AAAS, Missoula, Montana. (2) Pope K.O. (1997) Conf. Large Impacts & Planet. Evol. (Sudbury 1997), LPI Contrib. 922, 37-38. (3) Marshall J.R. et al. (1997) ISRU II Tech. Interchange Meet. LPI 1997, 27.

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# AEOLIAN SAND TRANSPORT IN THE PLANETARY CONTEXT: RESPECTIVE ROLES OF AERODYNAMIC AND BED-DILATANCY THRESHOLDS.

J.R. Marshall[1], J. Borucki[2], and C. Bratton[1], [1]SETI Institute, NASA Ames Research Center, MS 239-12, Moffett Field, CA 94035-1000, [2]NASA Ames Research Center.

The traditional view of aeolian sand transport generally estimates flux from the perspective of aerodynamic forces creating the airborne grain population, although it has been recognized (1) that "reptation" causes a significant part of the total airborne flux; reptation involves both ballistic injection of grains into the air stream by the impact of saltating grains as well as the "nudging" of surface grains into a creeping motion. Whilst aerodynamic forces may initiate sand motion, it is proposed here that within a fully-matured grain cloud, flux is actually governed by two thresholds: an aerodynamic threshold, and a bed-dilatancy threshold. It is the latter which controls the reptation population, and its significance increases proportionally with transport energy. Because we only have experience with terrestrial sand transport, extrapolations of aeolian theory to Mars and Venus have adjusted only the aerodynamic factor, taking gravitational forces and atmospheric density as the prime variables in the aerodynamic equations, but neglecting reptation.

The basis for our perspective on the importance of reptation and bed dilatancy is a set of experiments that were designed to simulate sand transport across the surface of a martian dune. Using a modified sporting crossbow in which a sand-impelling sabot replaced the bolt-firing mechanism, individual grains of sand were fired at loose sand targets with glancing angles typical of saltation impact; grains were projected at ~80 m/s to simulate velocities commensurate with those predicted for extreme martian aeolian conditions (2). The sabot impelling method permitted study of individual impacts without the masking effect of bed mobilization encountered in wind-tunnel studies. At these martian impact velocities, grains produced small craters formed by the ejection of several hundred grains from the bed. Unexpectedly, the craters were not elongated, despite glancing impact; the craters were very close to circular in planform. High-speed photography showed them to grow in both diameter and depth after the impactor had ricochetted from the crater site. The delayed response of the bed was "explosive" in nature, and created a miniature ejecta curtain spreading upward and outward for many centimeters for impact of 100-300 micron-diameter grains into similar material. Elastic energy deposited in the bed by the impacting grain creates a subsurface stress regime or "quasi-Boussinesq" compression field (Figure 1). Elastic recovery of the bed occurs by dilatancy; shear stresses suddenly convert the grains from closed to open packing, and grains are consequently able to eject themselves forcefully from the impact site. Random jostling of the grains causes radial homogenization of stress vectors and a resulting circular crater. There is a great temptation to draw parallels with cratering produced by meteorite impacts, but a rigorous search for common modelling ground between the two phenomena has not been conducted at this time.

For every impact of an aerodynamically energized grain, there are several hundred grains ejected into the wind for the high-energy transport that might occur on Mars. Many of these grains will themselves become subject to the boundary layer's aerodynamic lift forces (their motion will not immediately die and add to the creep population), and these grains will become indistinguishable from those lifted entirely by aerodynamic forces. As each grain impacts the bed, it will eject even more grains into the flow. A cascading effect will take place, but because it must be finite in its growth, damping will occur as the number of grains set in motion causes mid-air collisions that prevent much of the impact energy from reaching the surface of the bed -- thus creating a dynamic equilibrium in a high-density saltation cloud.

It is apparent from Figure 1 that for a given impact energy, the stress field permits a smaller volume of grains to convert to open packing as the size of the bed grains increases, or as the energy of the "percussive" grain decreases (by decrease in velocity or mass). Thus, the mass of the "repercussive" grain population that is ejected from the impact site becomes a function of the scale of the stress field in relation to the scale of the bed material (self-similarity being applicable if both bed size and energy are simultaneously adjusted). In other words, in a very high energy aeolian system where an aerodynamically raised grain can ballistically raise many more grains, the amount of material lifted into the wind becomes largely a function of a dilatancy threshold. If this threshold is exceeded, grains are repercussively injected into the saltation cloud. The "dilatancy threshold" may be defined in terms of the saltation percussive force required to convert the bed, through elastic response, from a closed to an open packing system. If open packing cannot be created, the grains cannot escape from the impact site, even though the elastic deformation and percussive force may be able to reorganize the grains with respect to one another. As the crossbow experiments showed, for an ever-increasing bed grain size, a point is reached when no material can be moved because the energy of the percussive grain is insufficient to dilate the relatively coarse bed. Although this seems to be stating the obvious -- that too little energy will not cause the bed to splash -- the consequences of exceeding the "splash threshold" by dilatancy are not so obvious for high-energy aeolian transport. It is noted that the force required to elastically dilate the bed has to overcome Coulombic grain attractions such as dipole-dipole coupling, dielectric, monopole, contact-induced dipole attractions, van der Waals forces, molecular monolayer capillary forces, as well as the mechanical interlocking frictional resistance of the grains.

On Mars, it is predicted that the dilatancy threshold may be the prime control of grain flux. On earth, the aerodynamic thresholds and dilatancy thresholds are of about equal importance (1). On Venus, the aerodynamic threshold dominates (Figure 2). Thus, aeolian transport of sand in the planetary context should be viewed as a variable combination of primarily these two thresholds, not simple a function of an aerodynamic threshold adjusted for gravity and atmospheric density.

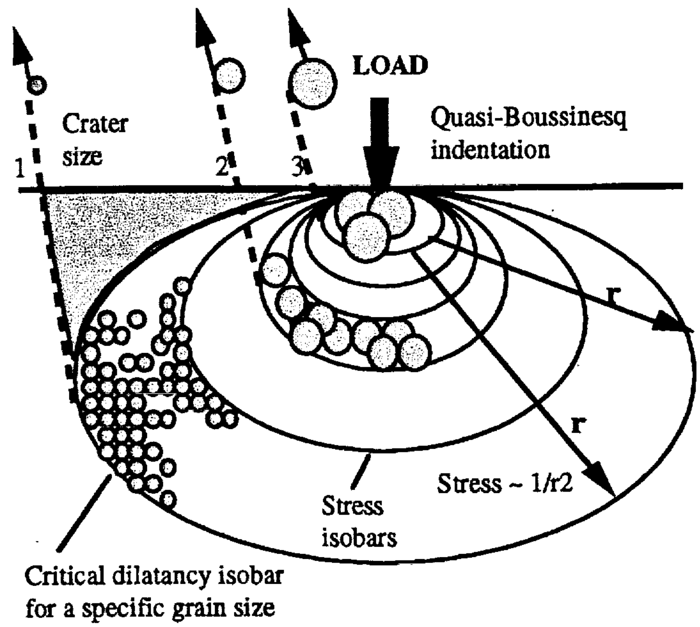


**Figure 1: Relationship of stress field magnitude to dilatable bed volume**

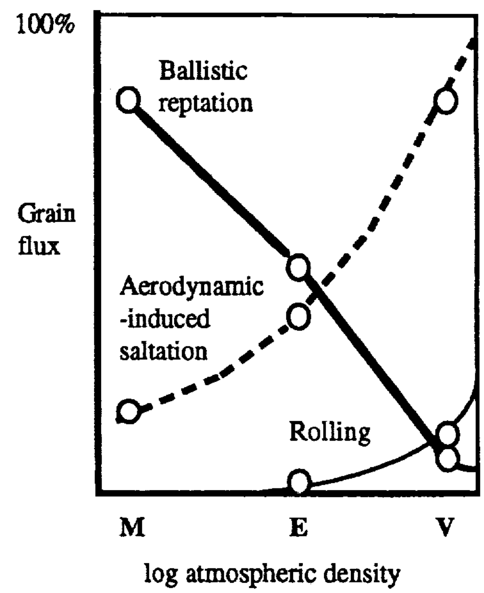


**Figure 2: Relative roles of flux modes for Mars, Earth, & Venus**

This work was supported by the NASA PG & G Program.

(1) Anderson R.S. (1987) Document BB-56, Univ. Washington. (2) Sagan C. (1973) JGR 78, 4155.

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 1999201873 (17/91 ABS ONLY

# STRATEGIES AND TECHNOLOGIES FOR IN SITU MINERALOGICAL INVESTIGATIONS ON MARS.

J.R. Marshall[1], C. Bratton[1], L. Koppel[2], M. Hecht[3], E. Metzger[4], [1]SETI Institute, MS 239-12, NASA Ames Research Center, Moffett Field, CA 94035-1000, [2]Oryx Technology Corporation, [3]Jet Propulsion Laboratory, [4]San Jose State University.

Surface landers on Mars (Viking and Pathfinder) have not revealed satisfying answers to the mineralogy and lithology of the planet's surface. In part, this results from their prime directives: Viking focused on exobiology, Pathfinder focused on technology demonstration. The analytical instruments on board the landers made admirable attempts to extract the mineralogy and geology of Mars, as did countless modeling efforts after the missions. Here we suggest a framework (Fig. 1) for elucidating martian, or any other planetary geology, through an approach that defines (a) type of information required, (b) explorational strategy harmonious with acquisition of these data, (c) interpretation approach to the data, (d) compatible mission architecture, (e) instrumentation for interrogating rocks and soil.

(a) Data required: The composition of a planet is ordered at scales ranging from molecules to minerals to rocks, and from geological units to provinces to planetary-scale systems. The largest ordering that in situ compositional instruments can attempt to interrogate is rock type (referred to in Fig. 1 as "aggregate" information. This is what the geologist attempts to identify first. From this, mineralogy can be either directly seen or inferred. From mineralogy can be determined elemental abundances and perhaps the state of the compounds as being crystalline or amorphous ("Order" in Fig.1). Knowledge of rock type and mineralogy is critical for elucidating geologic process. Mars landers acquired extremely valuable elemental data, but attempted to move from left to right within Fig. 1 -- from elements to aggregates -- but this can only be done by making many assumptions and sometimes giant leaps of faith. Data we believe essential are elements, minerals, degree of ordering of compounds, and the aggregate or rock type that these materials compose.

(b) Explorational strategy: A lander should function as a surrogate geologist. Of the total landscape, a geologist sees much, but gives detailed attention to an infinitesimally small amount of what is seen. To acquire samples worth detailed scrutiny, as many samples as possible need examining at a cursory or reconnaissance level. A representative, statistically-meaningful sample number cannot be overemphasized. ("n" dimension, Fig. 1). This maxim still applies to geological exploration of our own planet of which we have abundant knowledge. Analysis of many samples mandates low-power consumption per sample.

(c) Data interpretation: No single instrument can analyze the full spectrum of the x-axis in Fig. 1 . An instrument is optimized for detecting certain material characteristics and must therefore affix itself to some point on the x-axis. Any conclusions drawn about data to the left or right of the instrument's position on this axis must necessarily be derived by inference. Hence, it seems logical to include on a mission, instruments that are not closely spaced in their x-axis-position, and if only two analytical methods are used, as shown, they should start at opposite ends of the axis and work towards the center. As examples, we depict a high-resolution camera to evaluate rock type ("aggregate" state) and mineralogy, and an x-ray diffractometer-fluorescence spectrometer (XRD-XRF) to determine elements, minerals, and the degree of order of materials.

(d) Mission architecture: No instrument or suite of instruments can be relied upon to always give truly unequivocal analyses. The suite of instruments should therefore permit conclusions of one instrument to be checked against those of another through closed analytical loops. These "loops" can be structured by a combination of orbital imagery, descent imagery, broad-band site viewing/analysis, and data that cover both x and y axes in Fig. 1. For example, the detection of a basaltic-looking rock with a microscope should be checked against the elements detected, the appearance of the rock as a lava flow from descent imagery, and so forth.

(e) Instrumentation: To satisfy the above criteria, it is necessary to: (i) See the rock or soil with high resolution + magnification, (ii) Examine many samples, (iii) Consume little power per analysis, (iv) Determine elemental species, (v) Determine mineralogy directly (not inferentially) and the degree of ordering of compounds, (vi) Start analyzing from both ends of the x-axis in Fig. 1.

Every geologist wants to see the hand sample first, and apply a handlens to its surface. This has not been the starting point for missions to Mars. Thus, our technology of choice is depicted in Fig. 2: it satisfies all these criteria (1,2,3). This XRD-XRF-Optical instrument currently being developed, analyses rock or soil surfaces without the need for sample acquisition or preparation; this satisfies the power criterion, and enables many analyses. The device acquires direct mineralogy and determines elemental species. The embedded endoscopic camera satisfies the critical criterion of close inspection of samples; the fiber optic cable can also be used for IR, UV, or laser sample analysis.

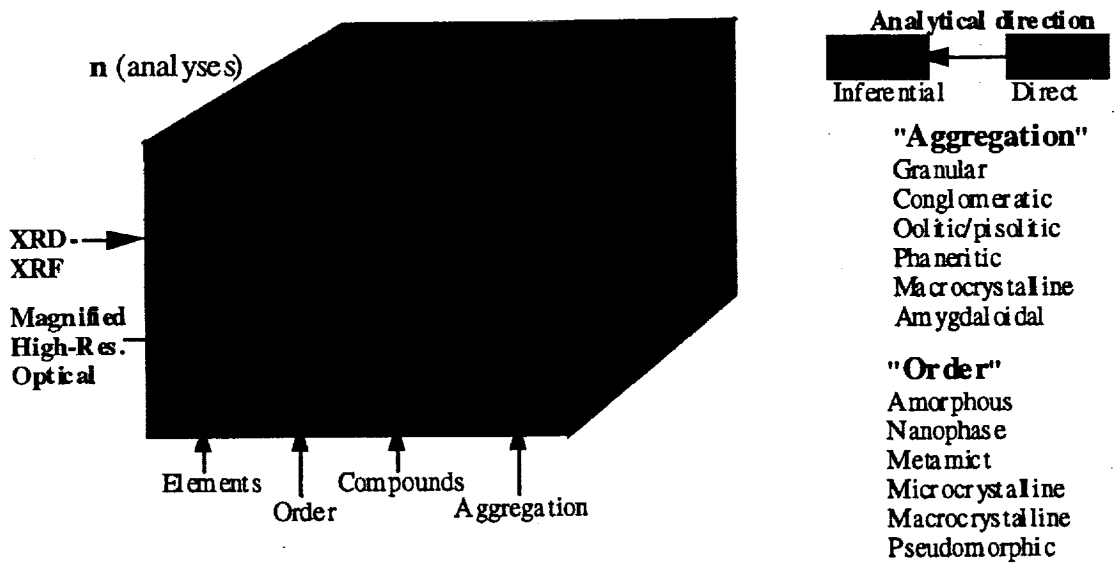
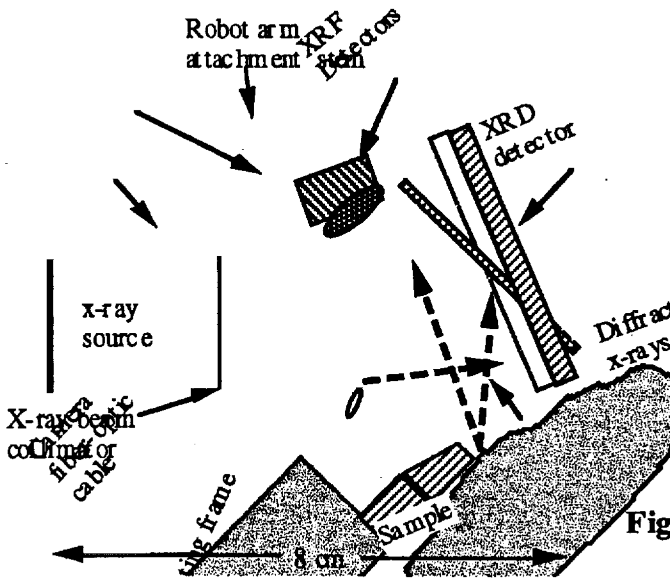



**Figure 1: Analytical framework for in situ exploration of a planetary surface**




| | |
|---|---|
| Mass | 0.3 kg |
| Volume | 200 cm3 |
| Energy consumption | 4500 J per sample |
| Analysis time XRD | 5 min per sample |
| Analysis time XRF | 10 min per sample |
| Analytical method | Proximity only |
| X-ray source | Ti target |
| X-ray power | 30 kV/0.3 A (9 W) |
| XRD detector | P-N junction photodiode monolithic array |
| XRF detector | Si PIN photodiode |
| d-spacing range | 1.4 to 25 angstroms |
| Element detection | Na to Br (C possible) |
| Camera | Board-mounted CCD |
| Optical resolution | 1x to 50x |

**Figure 2: XRD-XRF-Optical Instrument**

(1) Marshall J.R. (1997) ISRU II Tech. Interchange Meeting, LPI, 1997, 27. (2) Koppel L.N. & Marshall J.R. (1998) Rev. Sci. Instr. In press. (3) Marshall J.R. et al. (1996) LPSC XXVII, 815.

# "COULOMBIC VISCOSITY" IN GRANULAR MATERIALS: PLANETARY AND ASTROPHYSICAL IMPLICATIONS.

J.R. Marshall, SETI Institute, NASA Ames Research Center, MS 239-12, Moffett Field, CA 94035-1000.

The term "Coulombic viscosity" is introduced here to define an empirically observed phenomenon from experiments conducted in both microgravity, and in ground-based 1-g conditions. In the latter case, a sand attrition device was employed to test the longevity of aeolian materials by creating two intersecting grain-circulation paths or cells that would lead to most of the grain energy being expended on grain-to-grain collisions (simulating dune systems). In the areas in the device where gravitationally-driven grain-slurries recycled the sand, the slurries moved with a boundary-layer impeded motion down the chamber walls. Excessive electrostatic charging of the grains during these experiments was prevented by the use of an a.c. corona (created by a Tesla coil) through which the grains passed on every cycle. This created both positive and negative ions which neutralized the triboelectrically-generated grain charges. When the corona was switched on, the velocity of the wall-attached slurries increased by a factor of two as approximately determined by direct observation. What appeared to be a freely-flowing slurry of grains impeded only by intergranular mechanical friction, had obviously been significantly retarded in its motion by electrostatic forces between the grains; with the charging reduced, the grains were able to move past one another without a flow "viscosity" imposed by the Coulombic intergranular forces.

A similar phenomenon was observed during microgravity experiments aboard Space Shuttle in USML-1 & USML-2 spacelabs where freely-suspended clouds of sand were being investigated for their potential to form aggregates. In this environment, the grains were also charged electrostatically (by natural processes prior to flight), but were free from the intervention of gravity in their interactions. The grains were dispersed into dense clouds by bursts of air turbulence and allowed to form aggregates as the ballistic and turbulent motions damped out. During this very brief (30-60 sec) damping period, motion of the grains was observed to be retarded by the electrostatic interactions. The fact that the grains almost instantly formed aggregates was evidence that their ballistic motions had been constrained and redirected by the dipole-dipole interactions that led to filamentary aggregate development (1,2). Undoubtedly, the "Coulombic viscosity" of the cloud assisted in damping grain motion so rapidly.

The electrostatically-induced grain-cloud viscosity or drag exerted on grain motion, is a complex function of three major parameters: charge magnitude, charge sign, and mean intergranular distance. The above experiments illustrate one particular type of granular behavior. The discussion here will therefore be restricted to drag relationships: (a) between grains that are naturally charged triboelectrically and thus exhibit dipole-dipole attractions between one another even if there are slight net charges present (which can be overwhelmed by dipole coupling at short distances), and (b) between grains that are densely spaced where the intergranular distance varies between zero and some value (usually tens or hundreds of grain diameters) that permits each grain to detect the dipole moment of another grain -- the distance is not so great that other grains appears as neutral electrical "singularities".

**I. Aeolian transport:** During motion of grains in a saltation cloud (on Earth, Mars, or Venus), triboelectric charging must occur as a result of multiple grain contacts, and by friction with the entraining air. A situation might develop that is similar to the one described above in the attrition device: grain motion becoming significantly retarded (reduced flux) as grains find it increasingly difficult to either separate from the surface, or to pass one another without Coulombic retarding forces. A "Coulombic drag" will exist at flux initiation and increase with time to work in direct opposition to the aerodynamic drag that drives the grain motion. It is predicted that this will lead to an increase with time of both the aerodynamic and bed-dilatancy thresholds (3). Because of Paschen discharge effects in the martian atmosphere, the electrostatic charging in a saltation cloud may be partially abated, but this will lead to greater grain mobility, more charging, and thus to a charge-discharge steady state mediated by mechanical interactions.

**II. Dry colluvial systems:** Sand avalanches on dunes, dry debris flows, talus flows, avalanches, and pyroclastic surges are examples of gravity-driven, dense granular flows where rock/grain fragmentation and grain-to-grain interactions cause triboelectrification (sometimes augmented by other electrical charging processes), and where the grain densities of the systems are such that strong dipole-dipole interactions between grains might be expected to be present. Because it is expected that the Coulombic forces between grains will cause a sluggishness or enhanced granular-flow viscosity, the motion of a grain mass will be retarded or damped so that this will assist, ultimately, in terminating the flow. The greatest Coulombic viscosity will be created in the most highly charged systems, which will also be the most energetic. Thus, grain flows have some tendency to be self-limiting by internal energy partitioning; gravitational potential is converted to Coulombic potential, which manifests itself as a drag force between the grains.

**III. Volcanic eruption plumes and impact ejecta curtains:** The violence of these systems leads to powerful electrical charging of particulates. Lightning storms emanating from volcanic plumes are a testimony to the levels of charging. As pyroclastic grains interact forcefully and frequently within eruption plumes, it is reasonable to predict that the internal turbulent motions of the plume will be significantly damped by the Coulombic viscosity exerted by grain charges. Similarly, the high-velocity transport of ejecta caused by a meteorite impact should be subject to the conversion of kinetic energy into Coulombically-driven grain interactions that increase the viscosity of the debris cloud's motion.

**IV. Protoplanetary disks and planetary rings:** In both these systems, grains of all sizes are being gravitationally moved with speeds and directions commensurate with their size and position within the gravitational field. Hence, there are relative motions of grains with respect to one another. If the grains experience dipole-dipole interactions, these relative motions will be resisted, leading to an element of cloud viscosity caused by Coulombic forces. This will impact the behavior of the cloud, and thus influence the mode by which the ring particles interact, or the mode by which planetesimals form (3).

This work was supported by the NASA Exobiology Program.

(1) Marshall J.R. (1997) USML-2/USMP-3 L+1 Report, NASA CP, In press. (2) Marshall J.R. (1994) NASA CP 3272, 717-732. (3) Marshall J.R. This volume.

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1998 AGU Fall Meeting, San Francisco 19990201875 (19)/91 ABS. ONLY

# Dust on Mars: An Aeolian Threat to Human Exploration?

J. Marshall, SETI Institute, MS 239-12 NASA Ames Research Center, Moffett Field, CA 94035

The NASA HEDS Program is duly concerned for human explorers regarding the potential hazard posed by the ubiquitous dust mantle on Mars. To evaluate properties of dust that could be hazardous to humans, the MPS 2001 Lander payload will include the Mars Environmental Compatibility Assessment (MECA) experiment. This includes optical and atomic-force microscopy to evaluate soil grains for shape and size, wet chemistry to evaluate toxic substances, electrometry to evaluate triboelectric charging, and test-material palets to evaluate electrostatic and magnetic adhesion, and the hardness/abrasiveness of soil grains; these experimental subcomponents are delivered samples by the camera-equipped robotic arm of the lander which will acquire material from depths of 0.5 to 1.0 m in the soil. Data returned by MECA will be of value to both the HEDS and planetary/astrobiology communities. Dust poses a threat to human exploration because the martian system does not hydrologically or chemically remove fine particles that are being continuously generated by thermal, aeolian, and colluvial weathering, and by volcanism and impact over billions of years. The dust is extremely fine-grained, in copious quantities, ubiquitous in distribution, continually mobile, and a source of poorly-grounded static charges -- a suite of characteristics posing a particulate and electrical threat to explorers and their equipment. Dust is mobilized on global and regional scales, but probably also unpredictably and violently at local scales by dust devils. The latter might be expected in great abundance owing to near surface atmospheric instability (dust devils were detected by Pathfinder during its brief lifetime). Preliminary laboratory experiments suggest that space-suit materials subjected to windblown dust may acquire a uniform, highly adhesive dust layer that is also highly cohesive laterally owing to electrostatic forces. This layer will obscure visibility through the helmet visor, penetrate joints and fabrics, change the thermal properties of the suit, and possibly affect electronic/electrical suit functions. It is paramount that future missions address the issue of interparticle forces, and in particular, the role played by ionizing radiation in affecting these forces on Mars.

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# Compositional Analysis of Martian Soil: Synergism of APEX and MECA experiments on MPS 2001

R. Arvidson, Dept. of Earth and Planetary Sciences, Washington University, St Louis, MO 63130
J. Marshall, SETI Institute, MS 239-12 NASA Ames Research Center, Moffett Field, CA 94035

The APEX (ATHENA Precursor Experiment) payload for the Mars 2001 mission will analyze soil and dust with a multispectral panoramic imager and an emission spectrometer on a mast on the lander, a Moessbauer spectrometer on the lander robotic arm (RA), and APXS measurements on the Marie Curie rover. These analytical methods will provide data on elemental abundances and mineralogy. The MECA payload on the lander will apply microscopy, AFM, wet chemistry, adhesive substrates, and electrometry to determine the shape and size of particles in the soil and dust, the presence of toxic substances, and electrostatic, magnetic, and hardness qualities of particles. The two experiments will complement one another through several interactions: (1) The panoramic imager provides the geological setting in which both APEX and MECA samples are acquired, (2) The RA provides samples to MECA from the surface and subsurface and will permit APEX analytical tools access to materials below the immediate surface, (3) Comparisons can be made between elemental analyses of the Moessbauer, IR, APXS on APEX and the wet chemistry of MECA which will define trace elements (ionic species in solution) and soil redox potential and conductivity. (4) APEX bulk compositional measurements will place MECA trace measurements in context, and similarly, MECA microscopy will provide particle size data that may correlate with compositional differences determined by the APEX instruments. Additionally, lithic fragments viewed by the MECA microscope station should correlate with mineral/rock species inferred by APEX data, (5) If APEX instruments detect quartz for example, the scratch plates of the MECA microscope stage will define if a mineral of this hardness is registered during abrasion tests. This is by no means an exhaustive list of potential interactions, but it is clear that both the sheer number of analytical techniques and their complementarity should provide an analytically powerful capability for both planetary and HEDS communities.

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# Mars Environmental Compatibility Assessment (MECA) - Identifying the Hazards of the Martian Soil

T. P. Meloy[1], M. H. Hecht[2], M. S. Anderson[2], M. A. Frant[3], S. D. Fuerstenau[2], H. U. Keller[4], W. J. Markiewicz[4], J. Marshall[5] W. T. Pike[2], C. F. Quate[6], J. D. Rademacher[2], M. W. Shellman[2], W. W. Schubert[2], and P. Smith[7]

*1. W. Virginia University, 338 COMER, P.O. Box 6070, Morgantown, WV 26506 USA*
*2. Jet Propulsion Laboratory, 4800 Oak Grove Dr., Pasadena, CA 91109 USA*
*3. Orion Research, Inc., 131 Westchester Rd., Newton, MA USA*
*4. Max Planck Institut fur Aeronomie, Max-Planck-Str. 2, 37189 Katlenburg-Lindau, Germany*
*5. SETI Institute NASA ARC, M/S 239-12, Moffett Field, CA 94035-1000 USA*
*6. Stanford University, Ginzton Laboratory, Stanford, CA 94305-9045 USA*
*7. University of Arizona, Lunar and Planetary Laboratory, Túcson AZ 85721 USA*

Sometime in the next decade NASA will decide whether to send a human expedition to explore the planet Mars. The Mars Environmental Compatibility Assessment (MECA) has been selected by NASA to evaluate the Martian environment for soil and dust hazards to human exploration. The integrated MECA payload contains three elements: a wet-chemistry laboratory, a microscopy station, and enhancements to a lander robot-arm system incorporating arrays of material patches and an electrometer to identify triboelectric charging during soil excavation.

The wet-chemistry laboratory will evaluate samples of Martian soil in water to determine the total dissolved solids, redox potential, pH, and quantify the concentration of many soluble ions using ion-selective electrodes. These electrodes can detect potentially dangerous heavy-metal ions, emitted pathogenic gases, and the soil's corrosive potential.

MECA's microscopy station combines optical and atomic-force microscopy with a robot-arm camera to provide imaging over nine orders of magnitude, from meters to nanometers. Soil particle properties including size, shape, color, hardness, adhesive potential (electrostatic and magnetic), will be determined on the microscope stage using an array of sample receptacles and collection substrates, and an abrasion tool,. The simple, rugged atomic-force microscope will image in the submicron size range and has the capability of performing a particle-by-particle analysis of the dust and soil.

Although selected by NASA's Human Exploration and Development of Space Enterprise, the MECA instrument suite also has the capability to address basic geology, paleoclimate, and exobiology issues. To understand both contemporaneous and ancient processes on Mars, the mineralogical, petrological, and reactivity of Martian surface materials should be constrained: the MECA experiment will shed light on these quantities through its combination of chemistry and microscopy. On Earth, the earliest forms of life are preserved as microfossils. The atomic-force microscope will have the required resolution to image down to the scale of terrestrial microfossils and beyond.

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"Mars Exploration Programme & Sample Return Mission"
Conference, France, Feb. 1-5, 1999. 1999201878 (22/91 ABS. ONLY

# ORIGIN AND REACTIVITY OF THE MARTIAN SOIL: A 2003 MICROMISSION

Albert S. Yen[1] (ayen@mail1.jpl.nasa.gov), S. Sam Kim[2], John Marshall[3], and Bruce C. Murray[4]

[1] Jet Propulsion Laboratory, Mail Stop 183-501, 4800 Oak Grove Drive, Pasadena, CA 91109
[2] Jet Propulsion Laboratory, Mail Stop 183-401, 4800 Oak Grove Drive, Pasadena, CA 91109
[3] SETI Institute at MS 239-12, NASA Ames Research Center, Moffett Field, CA 94035
[4] California Institute of Technology, 150-21, 1200 E. California Blvd., Pasadena, CA 91125

## Scientific Objectives

The role of water in the development of the martian surface remains a fundamental scientific question. Did Mars have one or more "warm and wet" climatic episodes where liquid water was stable at the surface? If so, the mineral phases present in the soils should be consistent with a history of aqueous weathering. More generally, the formation of hydrated mineral phases on Mars is a strong indicator of past habitable surface environments. The primary purpose of this investigation is to help resolve the question of whether such aqueous indicators are present on Mars by probing the upper meter for diagnostic mineral species.

According to *Burns* [1993], the formation of the ferric oxides responsible for the visible color of Mars are the result of dissolution of $Fe^{2+}$ phases from basalts followed by aqueous oxidation and precipitation of $Fe^{3+}$ mineral assemblages. These precipitates likely included iron oxyhydroxides such as goethite (a-FeOOH) and lepidocrocite (g-FeOOH), but convincing evidence for these phases at the surface is still absent. The stability of these minerals is enhanced beneath the surface [*Pollack et al.,* 1970], and thus we propose a subsurface search for hydroxylated iron species as a test for a large-scale chemical weathering process based on interactions with liquid water.

It is also possible that the ferric minerals on Mars are not aqueous alteration products of the rocks. A chemical study of the Pathfinder landing site concluded that the soils are not directly derived from the surrounding rocks and are enhanced in Mg and Fe [*Rieder et al.*, 1997]. The additional source of these elements might be from other regions of Mars and transported by winds, or alternatively, from exogenic sources. *Gibson* [1970] proposed that the spectral reflectivity of Mars is consistent with oxidized meteoritic material. *Yen and Murray* [1998] further extend Gibson's idea and show, in the laboratory, that metallic iron can be readily oxidized to maghemite and hematite under present-day martian surface conditions (in the absence of liquid water). A test for a meteoritic component of the soil can be conducted, as described below, by searching for the presence of Ni at the martian surface. The average abundance of nickel in an Fe-Ni meteorite is ~7% and, if present at measurable levels in the soil, would be indicative of an exogenic contribution. In addition, it may be possible to directly search for mineral phases common in meteorites.

An understanding of the formation and evolution of the martian soil would not be complete without addressing the unusual reactivity discovered by the Viking Landers [*Oyama* *and Berdahl*, 1977; *Levin and Straat*, 1977]. The presence of an inorganic oxidant, possibly one produced as a results of photochemical processes, is the most widely accepted explanation of the Viking results. Are these chemical species simply adsorbed on soil grains, or have they reacted with the metal oxide substrates and altered the mineral structures? Could a completely different (non-photochemical) process be responsible for the soil reactivity? The various ideas for the nature of this putative oxidant could be constrained by a measurement of the change in reactivity with depth. Different compositions will have different lifetimes and mobilities and thus will have different vertical profiles. Because the oxidizing compounds are believed to actively destroy organic molecules, determination of the reactivity gradient also has significant implications for the search for life on Mars.

**Implementation Approach**

The most practical method for conducting the scientific investigations of the soil as described above for a 2003 micromission is by making modifications to the existing Deep Space 2 (DS2) microprobe design. DS2 micropenetrators are unique in their ability to provide easy access to subsurface samples. The current system is capable of penetrating to a depth of approximately 50 cm but can be readily modified to achieve depths of 1 meter or more. The other major change to the existing system would be a redesign of the telecommunications system so an efficient link to a relay orbiter can be established. The instrument complement we envision for this 2003 micromission includes a $^{57}Fe$ nuclear magnetic resonance (NMR) spectrometer to characterize iron minerals and to specifically look for oxyhydroxide phases, an X-Ray fluorescence (XRF) device to look for Ni in the soil, thin-film chemiresistors in the forebody and aftbody of the probe to measure the soil reactivity gradient, and possibly an X-Ray powder diffraction (XRD) instrument to search for signatures of exogenic minerals.

The NMR would be housed in the forebody to sample soils at depth that remain unaltered by the surface environment. Detection of iron minerals is accomplished by transmitting radio frequencies through a small window and looking for characteristic absorptions. An additional sensor and collecting magnet would be placed on the aftbody to identify the magnetic particles in the windblown materials. Figure 1 shows initial results from a 50 gram prototype instrument operating on a 9 volt battery. Work is ongoing to determine the absolute sensitivity limits of the device to the plausible iron oxides and oxyhydroxides on Mars.

Modifications to an X-Ray instrument concept [*Marshall et al.*, 1996] to be compatible with the DS2 constraints may be possible and may permit direct measurements of the Ni abundance in the martian soil. The basic instrument would be capable of making a calibrated X-Ray fluorescence measurement and would be carried in the aftbody of the probe. We are currently investigating the possibility of carrying a complete XRF/XRD instrument in the aftbody to characterize the mineralogy and to look more thoroughly for the signature of exogenic material.

Recent work with thin-film metallic chemiresistors has demonstrated the ability to sensitively measure small changes in oxidizing potential [*Yen*, 1998]. Metals are good conductors when unreacted, and insulators when oxidized to any of the stable oxides. Thin layers (~100 Å) of metal rapidly exhibit dramatic resistance changes when small fractions of a monolayer of metal are converted to metal oxide (see figure 2). An array of chemiresistors in the forebody can be compared to a similar set in the aftbody to characterize the reactivity changes with depth. In addition to this gradient information, the rate of oxidation of the different thin-films in the array can provide constraints on the composition of the oxidizing species.

### Summary

A DS2-based microprobe system can be instrumented for a 2003 micromission to investigate the origin and reactivity of the martian soil. These measurements would provide invaluable information regarding the climate history and exobiological potential of the planet. The NMR, X-Ray, and chemiresistor measurement approach described here embodies a highly synergistic and general set of soil interrogation methods for elements, compounds, and crystal structures and can also be applied to other geologic questions of interest. For example, if the capability for precise targeting of the probes is available, then in-situ investigations of suspected evaporite and hydrothermal deposits would be possible with the same set of instruments.

**Figure 1:** $^{57}$Fe nuclear magnetic resonance spectra from magnetite and hematite collected using a prototype in-situ instrument.

**Figure 2:** Resistance versus time for an iron chemiresistor. Nitrogen (with PPM-level impurities) is introduced at T=1 hour, and the film is exposed to air at T=15 hours. As the oxidative capability of the environment increases, the resistance across the film also increases.

**References**


Burns, R. G., *Geochimica et Cosmochimica Acta., 57*, 4555-4574, 1993.

Gibson, E. K., *Icarus, 13,* 96-99, 1970.

Levin, G. I. and P. A. Straat, *JGR, 82*, 4663-4667, 1977.

Marshall, J., C. Bratton, R. Keaten, C. Seward, L. Koppel, *LPSC, XXVII,* 815-816, 1996.

Oyama, V. I. and B. J. Berdahl, *JGR, 82*, 4669-4676, 1977.

Pollack, J. B., R. N Wilson, and G. G. Coles, *JGR, 75*, 7491-7500, 1970.

Rieder, R., T. Economou, H. Wanke, et al., *Science, 278,* 1771-1774, 1997.

Yen, A. S. and B. C. Murray, abstract presented at the 30th meeting of the DPS (AAS), 1998.

Yen, A. S., Caltech Ph.D. Thesis, 1998.

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"Mars Exploration Programme & Sample Return Mission"
Conference, France, Feb. 1-5, 1999. 1999201879 (34)/91 NASA ONLY MMF

# THE MSP '01 MARS ENVIRONMENTAL COMPATIBILITY ASSESSMENT (MECA)

M. H. Hecht[1], T. P. Meloy[2], M. S. Anderson[1], M. G. Buehler[1], M. A. Frant[3], S. M. Grannan[1], S. D. Fuerstenau[1], H. U. Keller[4], W. J. Markiewicz[4], J. Marshall[5], W. T. Pike[1] W. W. Schubert[1], and P. Smith[6]

*1. Jet Propulsion Laboratory, 4800 Oak Grove Dr., Pasadena, CA 91109 USA*
*2. W. Virginia University, 338 COMER, P.O. Box 6070, Morgantown, WV 26506 USA*
*3. Orion Research, Inc., 131 Westchester Rd., Newton, MA 02158 USA*
*4. Max Planck Institut fur Aeronomie, Max-Planck-Str. 2, 37189 Katlenburg-Lindau, Germany*
*5. SETI Institute, NASA ARC, M/S 239-12, Moffett Field, CA 94035-1000 USA*
*6. University of Arizona, Lunar and Planetary Laboratory, Tucson AZ 85721 USA*

The Mars Environmental Compatibility Assessment (MECA) will evaluate the Martian environment for soil and dust-related hazards to human exploration as part of the Mars Surveyor Program 2001 Lander. Sponsored by the Human Exploration and Development of Space (HEDS) enterprise, MECA's goal is to evaluate potential geochemical and environmental hazards that may confront future martian explorers, and to guide HEDS scientists in the development of high fidelity Mars soil simulants.

The integrated MECA payload contains a wet-chemistry laboratory, a microscopy station, an electrometer to characterize the electrostatics of the soil and its environment, and arrays of material patches to study the abrasive and adhesive properties of soil grains. The instrument will acquire soil samples with a robotic arm equipped with a camera. MECA will examine surface and subsurface soil and dust in order to characterize particle size, shape, hardness, and also physical characteristics that may provide clues to mineralogy. MECA will characterize soil/water mixtures with respect to pH, redox potential, total dissolved ions, and trace toxins. MECA will determine the nature of electrostatic charging associated with excavation of soil, and the influence of ionizing radiation on material properties. It will also observe natural dust accumulation on engineering materials. To accomplish these objectives, MECA is allocated a mass of 10 kg within an enclosure of 35 x 25 x 15 cm.

The Wet Chemistry Laboratory (WCL) consists of four identical cells that will accept samples from surface and subsurface regions accessible to the Lander's robotic arm, mix them with water, and perform extensive analysis of the solution. Ion-selective electrodes and related sensors will evaluate total dissolved solids, redox potential, pH, and the concentration of many soluble ions and gases in wet Martian soil. These electrodes can detect potentially dangerous heavy-metal ions, emitted pathogenic gases, and the soil's corrosive potential. Experiments will include cyclic voltammetry and anodic stripping voltammetry. Complementary to the Viking experiments, the chemical laboratory will characterize the water-soil solution rather than emitted gases. Nonetheless, through analysis of dissolved gases it will be able to replicate many of the Viking observations related to oxidants.

MECA's microscopy station combines optical and atomic-force microscopy (AFM) in an actively focused, controlled illumination environment to image particles from millimeters to nanometers in size. Careful selection of substrates allows controlled experiments in adhesion, abrasion, hardness, aggregation, magnetic and other properties. Special tools allow primitive manipulation (brushing and scraping) of samples. Soil particle properties including size, shape, color, hardness, adhesive potential (electrostatic and magnetic), will be determined using an array of sample receptacles and collection substrates. The simple, rugged atomic-force microscope will image in the submicron size range and has the capability of performing a particle-by-particle analysis of the dust and soil. On Earth, the earliest forms of life are preserved as microfossils. The atomic-force microscope will have the required resolution to image down to the scale of terrestrial microfossils and beyond.

Mounted on the end of the robot arm, MECA's electrometer actually consists of four types of sensors: an electric field meter, several triboelectricity monitors, an ion gauge, and a thermometer. Tempered only by ultraviolet-light-induced ions and a low-voltage breakdown threshold, the dry, cold, dusty martian environment presents an imposing electrostatic hazard to both robots and humans. The field meter will measure the ambient field on nearby objects while the triboelectric sensors, using identical circuitry, will measure the charge accumulated on test substances as they are dragged through the soil by the arm. The ion chamber, open to the environment, will sense both charged dust and free ions in the air. Over and above the potential threat to electronics, the electrostatic environment holds one of the keys to transport of dust and, consequently, martian meteorology.

Viewed with the robot arm camera, the abrasion and adhesion plates are strategically placed to allow direct observation of the interaction between materials and soils on a macroscopic scale. Materials of graded hardness are placed directly under the robot arm scoop to sense wear and soil hardness. A second array, placed on the lander deck, is deployed after the dust plume of landing has settled. It can be manipulated in a primitive fashion by the arm, first having dirt deposited on it from the scoop and subsequently shaken clean. A third array will passively collect dust from the atmosphere.

In addition to objectives related to human exploration, the MECA data set will be rich in information relevant to basic geology, paleoclimate, and exobiology issues. To understand both contemporaneous and ancient processes on Mars, the mineralogy, petrology, and reactivity of Martian surface materials should be constrained. The MECA experiment will shed light on these quantities through its combination of chemistry and microscopy. MECA will be capable of measuring the composition of ancient surface water environments, observing microscopic evidence of geological (and biological?) processes, inferring soil and dust transport, comminution and weathering mechanisms, and characterizing soil horizons that might be encountered during excavation.

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Paris (February) 1999 Micromissions (MARS) Meeting

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# SOIL ANALYSIS MICRO-MISSION CONCEPTS DERIVED FROM THE MSP '01 MARS ENVIRONMENTAL COMPATIBILITY ASSESSMENT (MECA)

M.H. Hecht[1], T.P. Meloy[2], M.S. Anderson[1], M.G. Buehler[1], M.A. Frant[3], S.M. Grannan[1], S.D. Fuerstenau[1], H.U. Keller[4], W.J. Markiewicz[4], J. Marshall[5], W.T. Pike[1] W.W. Schubert[1], P. Smith[6]

*1. Jet Propulsion Laboratory, 4800 Oak Grove Dr., Pasadena, CA 91109 USA*
*2. W. Virginia University, 338 COMER, P.O. Box 6070, Morgantown, WV 26506 USA*
*3. Orion Research, Inc., 131 Westchester Rd., Newton, MA 02158 USA*
*4. Max Planck Institut fur Aeronomie, Max-Planck-Str. 2, 37189 Katlenburg-Lindau, Germany*
*5. SETI Institute NASA ARC, M/S 239-12, Moffett Field, CA 94035-1000 USA*
*6. University of Arizona, Lunar and Planetary Laboratory, Tucson AZ 85721 USA*
*7. Univ. of Neuchâtel, P.O. Box 3 CH-2007, Neuchâtel, Switzerland*

The Mars Environmental Compatibility Assessment (MECA) will evaluate the Martian environment for soil and dust-related hazards to human exploration as part of the Mars Surveyor Program 2001 Lander. The integrated MECA payload contains a wet-chemistry laboratory, a microscopy station, an electrometer to characterize the electrostatic environment, and arrays of material patches to study abrasion and adhesion.

Heritage will be all-important for low cost micro-missions, and adaptations of instruments developed for the Pathfinder, '98 and '01 Landers should be strong contenders for '03 flights. This talk has three objectives: (1) Familiarize the audience with MECA instrument capabilities; (2) present concepts for stand-alone and/or mobile versions of MECA instruments; and (3) broaden the context of the MECA instruments from human exploration to a comprehensive scientific survey of Mars. Due to time limitations, emphasis will be on the chemistry and microscopy experiments.

Ion-selective electrodes and related sensors in MECA's wet-chemistry laboratory will evaluate total dissolved solids, redox potential, pH, and the concentration of many soluble ions and gases in wet Martian soil. These electrodes can detect potentially dangerous heavy-metal ions, emitted pathogenic gases, and the soil's corrosive potential, and experiments will include cyclic voltammetry and anodic stripping. For experiments beyond 2001, enhancements could allow multiple use of the cells (for mobile experiments) and reagent addition (for quantitative mineralogical and exobiological analysis).

MECA's microscopy station combines optical and atomic-force microscopy (AFM) in an actively focused, controlled illumination environment to image particles from millimeters to nanometers in size. Careful selection of substrates allows controlled experiments in adhesion, abrasion, hardness, aggregation, magnetic and other properties. Special tools allow primitive manipulation (brushing and scraping) of samples. Soil particle properties including size, shape, color, hardness, adhesive potential (electrostatic and magnetic), will be determined using an array of sample receptacles and collection substrates. The simple, rugged atomic-force microscope will image in the submicron size range and has the capability of performing a particle-by-particle analysis of the dust and soil. Future implementations might enhance the optical microscopy with spectroscopy, or incorporate advanced AFM techniques for thermogravimetric and chemical analysis.

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AGU Boston, June 1999 1999201881 (20)/91 ABS ONLY
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**AFM Studies of Lunar Soils and Application to the Mars 01 Mission.**

C. M. Weitz, M. S. Anderson (Jet Propulsion Laboratory, 4800 Oak Grove Drive, Pasadena, CA 91109; cweitz@jpl.nasa.gov; msanders@mail1.jpl.nasa.gov);
J. Marshall (SETI, MS 239-12, NASA Ames Research Center, Moffett Field, CA 94035; jmarshall@mail.arc.nasa.gov).

The upcoming Mars 01 mission will carry an Atomic Force Microscope (AFM) as part of the Mars Environmental Compatibility Assessment (MECA) instrument. By operating in a tapping mode, the AFM is capable of sub-nanometer resolution in three dimensions and can distinguish between substances of different compositions by employing phase contrast imaging. To prepare for the Mars 01 mission, we are testing the AFM on a lunar soil to determine its ability to define particle shapes and sizes and grain-surface textures. The test materials are from the Apollo 17 soil 79221, which is a mixture of agglutinates, impact and volcanic beads, and mare and highland rock and mineral fragments. The majority of the lunar soil particles are less than 100 microns in size, comparable to the sizes estimated for martian dust [Rover Team, Science 278, 1765-1768, 1997].

We have used the AFM to examine several different soil particles at various resolutions. The instrument has demonstrated the ability to identify parallel ridges characteristic of twinning on a 150 micron plagioclase feldspar particle. Extremely small (10-100 nanometer) adhering particles are visible on the surface of the feldspar grain, and they appear elongate with smooth surfaces. Phase contrast imaging of the nanometer particles shows several compositions to be present. When the AFM was applied to a 100 micron glass spherule, it was possible to define an extremely smooth surface; this is in clear contrast to results from a basalt fragment which exhibited a rough surface texture. Also visible on the surface of the glass spherule were chains of 100 nanometer and smaller impact melt droplets.

For the '01 Mars mission, the AFM is intended to define the size and shape distributions of soil particles, in combination with the MECA optical microscope system and images from the Robot Arm Camera (RAC). These three data sets will provide a means of assessing potentially hazardous soil and dust properties. The study that we have conducted on the lunar soils now suggests that the MECA experiment will be able to define grain transport and weathering processes. For example, it should be possible to determine if Martian grains have been subjected to aeolian or water transport, volcanic activity, impact melting processes, in-situ weathering, and a host of other processes. Additionally, textural maturity could be assessed (via freshness and form of fracture patterns and grain shapes). Thus, the AFM has the potential to shed new light on Martian surface processes by adding the submicroscopic dimension to planetary investigations.

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# MICROGRAVITY EXPERIMENTS TO EVALUATE ELECTROSTATIC FORCES IN CONTROLLING COHESION AND ADHESION OF GRANULAR MATERIALS

J. Marshall[1], M. Weislogel [2], and T. Jacobson[2], [1]SETI Institute, NASA Ames Research Center, MS 239-12, Moffett Field, CA 94035-1000; jmarshall@mail.arc.nasa.gov, [2] NASA Lewis Research Center MS 500/102, Cleveland, OH 44135

The bulk behavior of dispersed, fluidized, or undispersed stationary granular systems cannot be fully understood in terms of adhesive/cohesive properties without understanding the role of electrostatic forces acting at the level of the grains themselves. When grains adhere to a surface, or come in contact with one another in a stationary bulk mass, it is difficult to measure the forces acting on the grains, and the forces themselves that induced the cohesion and adhesion are changed. Even if a single grain were to be scrutinized in the laboratory, it might be difficult, perhaps impossible, to define the distribution and character of surface charging and the three-dimensional relationship that charges (electrons, holes) have to one another.

The hypothesis that we propose to test in microgravity (for dielectric materials) is that adhesion and cohesion of granular matter are mediated primarily by dipole forces that do not require the presence of a net charge; in fact, nominally electrically neutral materials should express adhesive and cohesive behavior when the neutrality results from a balance of positive and negative charge carriers. Moreover, the use of net charge alone as a measure of the electrical nature of grain-to-grain relationships within a granular mass may be misleading. We believe that the dipole forces arise from the presence of randomly-distributed positive and negative fixed charge carriers on grains that give rise to a resultant dipole moment. These dipole forces have long-range attraction. Random charges are created whenever there is triboelectrical activity of a granular mass, that is, whenever the grains experience contact/separation sequences or friction.

Electrostatic forces are generally under-estimated for their role in causing agglomeration of dispersed grains in particulate clouds, or their role in affecting the internal frictional relationships in packed granular masses. We believe that electrostatic, in particular dipole-mediated processes, are pervasive and probably affect, at some level, everything from astrophysical-scale granular systems such as interstellar nebulae, protoplanetary dust and debris disks, planetary-scale systems such as debris palls from meteorite impact, volcanic eruptions, and aeolian dust storms, all the way to industrial-scale systems in mining, powder and grain processing, pharmaceuticals, and smoke-stack technologies. NASA must concern itself with the electrostatic behavior of dust and sand on Mars because of its potentially critical importance to human exploration. The motion and adhesion of martian surface materials will affect the design and performance of spacesuits, habitats, processing plants, solar panels, and any externally exposed equipment such as surface rovers or communication and weather stations. Additionally, the adhesion of dust and sand could greatly enhance contact with the potentially toxic components of the martian soil.

We have demonstrated /1,2/ in previous microgravity experiments (USML-1 & USML-2) that dipole forces give rise to the rapid conversion of particulate clouds into populations of aggregates (most commonly, filamentary in form). Because filaments appear to be recurring building structures for aggregates, and because of their probable ubiquity in particulate clouds, they are worthy of study for this reason alone. However, both the filaments themselves and the way they respond to electrical fields provide valuable clues to electrostatic forces acting in granular matter. We therefore propose that a very good method of probing the electrostatic character of granular material, in a non-intrusive way, is to allow grains and aggregates to express their interactions through unconstrained motions (acceleration/drift rates, repulsions, attractions) while they are freely suspended under microgravity conditions as part of a dispersed cloud. The motions would be induced by controlled electrical (homogeneous and inhomogeneous) fields and variable degrees of electrical neutralization of the grain cloud.

Thus, the dispersion and protracted suspension of grains is the "tool" of choice for interrogating individual grains regarding their electrostatic properties. In particular, filamentary aggregation of grains in a cloud is a powerful method for determining electrical polarization effects, and relationships between monopole and dipole forces, using growth rates, morphology, and especially the rotational and translational motions of aggregates as diagnostic expressions of the forces at work. Because different electrostatic forces cause different types of motion, this method enables each force to be isolated for study. Experimental investigations will be achieved by modifications to hardware that has already been successful deployment on two USML missions and laid much of the groundwork for the proposed research. Making relatively straightforward modifications to existing flight hardware provides a cost-effectiveness to the research effort.

Substantial progress has been made during the first year of the project; operations are proceeding through two parallel efforts -- scientific experiments and modeling are being studied by the PI (J. Marshall) at NASA Ames, while technical implementation of the project is being studied at LeRC, under the direction of M. Weislogel. At LeRC, an experiment development team has been formed to work with the PI for the identification of the "tall poles" in the design of the experiment. In concert with the PI, the team has worked to quantify the specific science requirements, and will conduct preliminary proof-of-concept tests as necessary. The team will establish the carrier options based on an early assessment of the hardware necessary to meet the science requirements. Several concepts have already been proposed. These are being reviewed in light of the cost/benefit of an automated verses crew-interactive test apparatus.

The primary science data are obtained by measuring the rates of formation, drift, and rotation of aggregates which form during the experiment procedures. The three-dimensional orientation of the aggregates is also valuable information as are the orientation and density of adhered particles/aggregates to the solid surfaces of the test apparatus. A statistically meaningful population is necessary to draw connections between theory and experiment. Thus, the challenge to designing an experimental apparatus to accomplish the above measurements is to provide a well-characterized "electrostatically clean" test chamber within which an imaging system can record 3-D particle behavior.

Secondary design issues concern the initial dispersion of particles, the ability to control local particle density, variable voltage supply and measurement for the aggregate "manipulators", and the ability to neutralize charged particles. Although several of these issues have been addressed in previous tests by the PI, the cell size, electrostatic shielding techniques, voltage levels, and the particle dispersion-neutralization procedures need to be addressed in proof tests to be performed at NASA LeRC in the coming months. These tests can be performed in the low-g environment of the KC-135 aircraft without significant effort; particle dispersion tests can be performed in simple drop tower experiments. The tests will enable quantitative descriptions of the science requirements for the flight experiment hardware. They will also buttress the fundamental scientific arguments to be presented during NASA's Science Concept Review (SCR) of the experiment.

At Ames, advances have been made in four areas:

(1) Three new models for the behavior of granular materials have been developed by the PI /3,4,5/, and were presented at the Lunar & Planetary Science Conference at LPI/NASA JSC in

March of 1998: (i) As a direct implication of both microgravity aggregation experiments and ground-based slurry-flow experiments conducted previously by the PI, it is suggested that electrostatic interparticle forces impose a "Coulombic friction" in the motion of grains in clouds, fluidized beds, or granular slurries and flows. Neutralized materials flow faster and become more sluggish" as triboelectric charging occurs. Ionized grain populations where grains may repel one another from acquiring like charges, could result in even lower resistance to motion than even a neutralized grain population, (ii) A densely-populated, triboelectrically charged monodispersed cloud of particulates cannot exist in a steady state unless it is in dynamic equilibrium with continuous mechanical disturbance (kinetic energy input). Inherently, the cloud collapses to an aggregated state, and then collapses further if the aggregates are disturbed. These changes of state have almost exact parallels with phase changes in gas-liquid-solid transitions because they occur precipitously, and they involve densification and energy release. The term "electrostructural phase changes" has been coined to describe the phenomenon, (iii) A model for planetary aeolian transport has been proposed which suggests that flux of windblown material is a function of both aerodynamic and bed-dilatancy thresholds; the latter is controlled by elastic energy release and confinement by electrostatic interparticle forces.

(2) Computer modeling efforts have been initiated by the PI to expand upon previous computer replication of filamentary aggregates using the dipole model. In the new work, the number of charge carriers on a grain will be varied so that dipole and monopole interactions become increasingly competitive; sudden behavioral transitions are expected. Once the algorithms have been developed (by T. Sauke of the SETI Institute), they will form the template for modeling the behavior of aggregates in any proposed engineering design for the microgravity experiment. Computer modeling (by D. Stratton of the SETI Institute) has also been initiated to test the cascading flux effect caused by the reptation grain population in the aeolian model just noted.

(3) A sand circulating device has been constructed in the laboratory at Ames to induce triboelectrification of an energetic grain population. This is intended to corroborate the future microgravity work by testing the limits of the dipolarization. At peak triboelectric charge saturation, the Coulombic viscosity of the population might decrease because the dipole moments becomes weakened by the "washing-out" effect of so many charge carriers on the grain surfaces.

(4) Experiments with the same device will be conducted in partnership with W. Farrell at NASA Goddard to determine the exchange of charge carriers between grains using RF signals as indicators of nanoscale electrical discharging.

**References:**

(1) Marshall, J. Particle Dispersion Experiment (PDE). NASA Conf. Publ. 3272 (II) (Ramachandran et al., eds.) 717732 (1994).

(2) Marshall, J., Freund, F., & Sauke, T. Catastrophic collapse in particulate clouds: Implications from aggregation experiments in the USML-1 and USML-2 Glovebox. USML-2/USMP-3 Launch Plus-One-Year Conf., NASA CP, in press (1998).

(3) Marshall, J. "Coulombic viscosity" in granular materials: Planetary and astrophysical implications. LPSC XXIX, 1135 (1998).

(4) "Electrostructural phase changes" in charged particulate clouds; Planetary and astrophysical implications. LPSC XXIX, 1132 (1998).

(5) Marshall, J., Borucki, J. & Sagan, C. Aeolian sand transport in the planetary context: Respective roles of aerodynamic and bed-dilatancy thresholds. LPSC XXIX, 1131 (1998).

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# MARS 2001 MISSION: ADDRESSING SCIENTIFIC QUESTIONS REGARDING THE CHARACTERISTICS AND ORIGIN OF LOCAL BEDROCK AND SOIL

R. S. Saunders1, R. E. Arvidson[2], C. M. Weitz[1], J. Marshall[3], S. W. Squyres[4], P. R. Christensen[5], T. Meloy[6], and P. Smith[7], [1]Jet Propulsion Laboratory, 4800 Oak Grove Drive, Pasadena, CA (saunders@scn1.jpl.nasa.gov); [2]Washington University, St. Louis; [3]SETI Institute/NASA Ames Research Center, Moffett Field, CA; [4]Dept. of Astronomy, Cornell University, Ithaca, NY; [5]Dept. of Geology, Arizona State University, Tempe, AZ.; [6]University of W. Virginia, Morgantown, WV; [7]University of Arizona, Tucson, AZ.

**Introduction**: The Mars Surveyor Program 2001 Mission will carry instruments on the orbiter, lander and rover that will support synergistic observations and experiments to address important scientific questions regarding the local bedrock and soils. The martian surface is covered in varying degrees by fine materials less than a few mms in size. Viking and Pathfinder images of the surface indicate that soils at those sites are composed of fine particles [1, 2]. Wheel tracks from the Sojourner rover suggest that soil deposits are composed of particles <40 mm [3]. Viking images show that dunes are common in many areas on Mars [4, 5, 6] and new MOC images indicate that dunes occur nearly everywhere[7]. Dunes on Mars are thought to be composed of 250-500 microns particles based upon Viking IRTM data and Mars wind tunnel experiments [8, 9, 10]. If martian dunes are composed of sand particles >100 microns and soils are dominated by <10 micron particles, then where are the intermediate grain sizes? Have they been worn away through prolonged transport over the eons? Were they never generated to begin with? Or are they simply less easy to identify because do they not form distinctive geomorphic features such as dunes or uniform mantles that tend to assume superposition in the soil structure?

**Questions about the martian soil**: Some top level scientific issues regarding the surface materials are: 1) What are the characteristics and origin of local bedrock and soil? It will be important to identify soil components that are part of the globally homogenized sediments and those that are locally derived. Are the locally derived soils related to rocks at the scene and are they more or less weathered than local rocks? What do the local rocks and soils reveal about the climate and weathering history of the site? 2) What are the processes that indurate the soil to produce duricrust? Is the process related to films of water that evaporate and leave mineral deposits or is the agent entirely volcanic, with ash deposits cemented on deposition? 3) What is the source and nature of the apparently ubiquitous sands. Sand and dust tend to occupy completely different sedimentological niches since they are transported by different mechanisms, saltation versus suspension. Sand and dust deposits tend to be well sorted in size and of generally uniform composition. What is the size distribution of the various surface materials? What is their composition? Are there microscopic surface features that reveal sedimentary history and environments?

**Experiments using the 2001 Mission Payload:** There are several landed and orbiting instruments on the 2001 Mission that will be used to address the scientific question of martian surface materials: The orbiter carries a gamma ray spectrometer (GRS) (Wm Boynton, UAZ, Team Leader) and a thermal emission imaging system (THEMIS) (P. Christensen, AZ State U, PI). The GRS will provide a global map of elemental abundance and hydrogen with a spatial resolution of about 300 km. The GRS data has the potential for adding information about the regional context of the landing site, but because of the low spatial resolution, local site information will not be possible. However, THEMIS will provide a multispectral IR image with 100 m resolution and the integrated imager will provide 20 m visible wavelength images. With these data we will be able to determine the mineralogical composition of the region around the landing site for minerals whose abundance is greater than 10%. This information will be used in conjunction with lander observations, discussed below, to characterize the mineralogy and composition of surface materials at the landing site. In addition, the THEMIS data will provide important clues to the grain size of the surface materials through their thermal properties. During descent, a camera on the lander, the Mars Descent Imager (MARDI) (M. Malin, Malin Space Systems, Team Leader) will provide a nested set of images from about 10 km height down to the surface with a resolution from about 10 m to a few cm near the surface. These images will be used to locate the lander and to guide rover operations.

The lander and rover carry instruments to image in the IR and visible range surface materials at several resolutions, and determine the chemical and elemental composition. MECA (Mars Environmental Compatibility Assessment) (T. Meloy, WVU, PI) has four separate experiments that will study the soil. (1) A wet chemistry lab will mix a small amount of soil with water to measure the total dissolved solids, redox potential, and pH of the soil. These results can be used to determine the soil composition and identify carbonates, evaporites, and salts in the soil.

(2) An optical and an atomic force microscope will be used to study individual grains and aggregates in the soil with resolutions of nanometers to millimeters. The optical microscope can be used to see the 3-D shape of grains while substrates on the microscope stage will be used to test hardness of grains for compositional identification, as well as magnetic nd electrostatic properties. The atomic force microscope will determine the shape and topography of ndividual grains and possibly distinguish between grains of different compositions. Determining the texture and shape of soil particles will be critical for understanding their origin, such as rounded particles supporting an origin by fluvial activity or as impact glasses whereas a jagged texture suggestive of an origin by chemical weathering or explosive volcanism. The size distribution in the martian soil will also be measured by the two microscopes. (3) Three abrasion patches on the 01 lander will be similar to patches on the Pathfinder lander [11] and used to determine adhesion and magnetic properties of atmospheric dust. (4) An electrometer on the robot arm will measure triboelectric charging as the arm digs into the martian soil, and will also determine electrical fields around the lander, static charges on soil, and atmospheric ion populations. By studying the soil with these four experiments, MECA will also identify potential hazards for future human explorers.

The Robotic Arm Camera (RAC) (Max Planck Institute and UAZ) has three color filters that will be used to observe trenches dug into the martian soil by the robotic arm. The RAC will also take images of the soil surface and dust deposited on the MECA patches. These high-resolution images can provide insight into the stratigraphy of the soil and fine-scale textures of particles in the soil. The Athena Precursor Experiment (APEX) (S. Squyres, Cornell, PI) has several instruments that will study the soil, including a stereo color PanCam, a mini-Thermal Emission Spectrometer (mini-TES), and a Mossbauer Spectrometer. The Pancam will be used to identify any drifts or dunes at the site and the color information can be used to classify variations in the soils. Mini-TES will be able to measure the spectral signature of the soil at 5-28 mm wavelengths. Any spectral differences detected in the soil may reflect compositional variations. Soils that are composed of Fe-bearing minerals can be analyzed by the Mossbauer spectrometer. The Marie Curie rover (the Pathfinder Sojourner engineering backup, built at JPL) will carry an Alpha Proton X-Ray Spectrometer (APXS) and cameras as part of the APEX experiment. The APXS will perform elemental analyses of the martian soil for comparison to soils at the Pathfinder and Viking sites. Rover wheel tests in the soil will also be performed to characterize the size of particles in the soil and their adhesive properties.

A large number of instruments and other experiments will be brought to bear on the major scientific questions. By using the Mini-TES and PanCam to identify and characterize materials near the lander, in reach of the Robotic Arm, and then measuring the elemental composition with the APXS, and finally collecting the same surface material with the RA scoop and delivering it to the MECA instruments, we can fully characterize the materials near the lander and begin to address the important scientific topics outlined above. The orbital data from THEMIS and GRS will allow us to put the detailed surface observations into a regional geologic context. Discussion: Viking and Pathfinder results seem to support an old age for the martian soil, probably created when erosion rates were higher and fluvial activity occurred. However, it has also been proposed that the soil may still be forming under current conditions by eolian activity [12], chemical weathering [13], and explosive volcanism [14]. It is still unclear how many processes contributed to soil development on Mars or if one process dominated. It is also important to know if the processes that created sand are different from those that produced dust. If the soils formed at different times in martian history then each may have a distinct trace element signatures that can be measured [15].

In summary, results from the '01 mission will greatly improve our knowledge of the martian soil by analyzing individual grains to determine their size, shape, and composition, thereby helping to understand the processes responsible for soil development on Mars. For a discussion of how these experiment synergies will be accomplished see a companion abstract in this conference [16], Mars 2001 Mission: Increasing Payload Synergies Through Coordinated Operations Planning and Implementation.

**References**: [1] Moore, H. J. et al. (1977) JGR, 82, 4497 [2] Golombeck et al. (1997) Science, 278, 1743 [3] Rover Team (1997) Science, 278, 1765 [4] Cutts, J. A., and R. S. U. Smith (1973) JGR, 78, 4139 [5] Breed, C. S., M. J. Grolier, and J. F. McCauley (1979) JGR, 84, 8183 [6] Greeley, R, N. Lancaster, S. Lee, and P. Thomas (1992) in Mars, pp. 730 [7] Malin et al. (1998) Science, 279, 1681 [8] Haberle R.M., and B. M. Jakosky (1991) Icarus, 90,187 [9] Edgett, K. S., and P. R. Christensen (1991) JGR, 96, 22765 [10] Greeley, R. and J. D. Iversen (1985) Wind as a Geological Process [11] Hviid, S. F. et al. (1997) Science, 278, 1768 [12] Smith, P. H. et al. (1997) Science, 278, 1758 [13] Banin, A., F. X. Han, I. Kan, and A. Cicelsky (1997) JGR, 102, 13341 [14] Edgett, K. S. (1997) Icarus, 130, 96 [15] Newsome, H. E., and J. J. Hagerty (1997) JGR, 102, 19345 [16] Arvidson et al., 1999, LPSC 30.

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# MARS 2001 LANDER MISSION: MEASUREMENT SYNERGY THROUGH COORDINATED OPERATIONS PLANNING AND IMPLEMENTATION

R. Arvidson[1], J. F. Bell III[2], D. Kaplan[3], J. Marshall[4], A. Mishkin[5], S. Saunders[5], P. Smith[6], S. Squyres[2], [1]Department of Earth and Planetary Sciences, Washington University, St. Louis, MO, arvidson@wunder.wustl.edu, [2]Cornell University, Ithaca, NY, [3]Johnson Space Center, Houston, TX, [4]SETI Institute/NASA Ames Research Center, Moffett Field, CA, [5]Jet Propulsion Laboratory, Pasadena, CA, [6]University of Arizona, Tucson, AZ.

The 2001 Mars Surveyor Program Mission includes an orbiter with a gamma ray spectrometer and a multispectral thermal imager, and a lander with an extensive set of instrumentation, a robotic arm, and the Marie Curie Rover [1]. The Mars 2001 Science Operations Working Group is a subgroup of the Project Science Group that has been formed to provide coordinated planning and implementation of scientific observations, particularly for the landed portion of the mission. The SOWG will be responsible for delivery of a science plan and, during operations, generation and delivery of conflict-free sequences. This group will also develop an archive plan that is compliant with Planetary Data System (PDS) standards, and will oversee generation, validation, and delivery of integrated archives to the PDS. In this report we cover one element of the SOWG planning activities, the development of a plan that maximizes the scientific return from lander-based observations by treating the instrument packages as an integrated payload.

Scientific objectives for the lander mission have been defined in [2]. They include observations focused on determining the bedrock geology of the site through analyses of rocks and also local materials found in the soils, and the surficial geology of the site, including windblown deposits and the nature and history of formation of indurated sediments such as duricrust. Of particular interest is the identification and quantification of processes related to early warm, wet conditions and the presence of hydrologic or hydrothermal cycles. Determining the nature and origin of duricrust and associated salts is very important in this regard. Specifically, did these deposits form in the vadose zone as pore water evaporated from soils or did they form by other processes, such as deposition of volcanic aerosols? Basic information needed to address these questions includes the morphology, topography, and geologic context of landforms and materials exposed at the site, together with quantitative information on material mineralogy, chemistry, and physical properties (rock textures; soil grain size and shape distributions; degree and nature of soil induration; soil magnetic properties). Table 1 summarizes how observations from the APEX [3], MECA [4], and MIP [5] Experiments, including use of the robotic arm, robotic arm camera (RAC, [6]), and the Marie Curie rover, will be used to address these parameters in a synergistic way. Not shown are the calibration and magnet targets for APEX and patch plates for MECA. The calibration targets provide radiometric and mineralogical control surfaces. The magnets allow observations of magnetic phases. Patch plates are imaged to determine adhesive and abrasive properties of soils.

Coordinated mission planning is crucial for optimizing the measurement synergy among the packages included on the lander. This planning has already begun through generation of multi-sol detailed operations activities.

One focus has been to develop a scenario to use the arm to dig a soil trench to a depth of tens of centimeters. The activity will be monitored through use of Pancam and RAC to ensure nominal operations and to acquire data to determine subsurface physical properties (e.g., angle of repose of trench walls). Pancam and Mini-TES observations would also provide constraints on mineralogy and texture for the walls and bottom of the trench during excavation. If desired, soils excavated at depth could be deposited on the surface and Mössbauer and APXS measurements could be acquired for these materials. Soil samples from various depths would be delivered to MECA for characterization of aqueous geochemistry and physical properties of soil grains, particularly size, shape, and hardness. These physical properties would be determined by optical and atomic force microscopy. When completed, detailed information of soil properties as a function of depth would be obtained. These various data sets would constrain our understanding of whether or not there are systematic variations in soil characteristics as a function of depth. These variations might be related, for example, to evaporative moisture losses and formation of salt deposits, thereby indicating water transport processes occurred fairly recently.

Many other value-added measurement scenarios are being developed. For example, characterizing the nature and dynamics of dust deposition will be done using MIP/DART to provide deposition rates, Pancam and RAC imaging of lander and rover surfaces to extrapolate these measurements to other areas, and a variety of measurements to determine if the bulk loose soil has the same characteristics as dust that accumulates during the mission.

Bedrock geology of the site is primarily an APEX-focu setting, mineralogy, and texture, and APXS data to be use interest will be to determine the extent to which rock hydrothermal processes, given that APEX is the precursor and 2005 rover missions [7].

**References:** [1,2] Saunders et al., *LPS XXX*, submitted al., *LPS XXX*, submitted. [5] Kaplan et al., *LPS XXX*, submi al. (1998) *LPS XXIX*, 1101.

*Table 1. Measurement Synergy Summary*

| **Observation** | **Relevance** |
|---|---|
| APEX Pancam multi-spectral, stereo images of site | Geologic setting; topography; spectrophotometric constrains on soil and rock mineralogy and texture; operations planning for arm and rover activities and monitoring dust accumulation on DART/MIP |
| APEX Mini-TES emission spectra for areas viewed by Pancam and acquired during diurnal thermal cycle | Mineralogy and texture of soils and rocks through analyses of spectral and thermophysical modeling |
| RAC color stereo images | Detailed views of areas available for digging with robotic arm; close-up views of soil in arm scoop and MECA patch plates |
| Robotic Arm and arm (MECA) electrometer | Soil physical properties based on analyses of motor currents generated during digging, images of trenches; delivery of soil to MECA; placement of $Fe^{57}$ Mössbauer Spectrometer onto surfaces. |
| APEX $Fe^{57}$ Mössbauer Spectrometer | Soil and rock iron oxidation state and mineralogy for areas accessible by arm |
| MECA Wet Chemistry | Aqueous geochemistry for arm-delivered surface and subsurface soil samples |
| MECA Microscopy | Soil size and shape distribution, constrains on mineralogy |
| MIP/DART | Windblown dust deposition rate and adhesive properties |
| APEX APXS on Marie Curie | Elemental abundances for rocks and soils |
| Marie Curie | Use of track patterns and soil physical property experiments (e.g. wheel spins) to constrain grain size distribution, degree of induration; close-up imaging |

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# COMPUTER MODELING OF ELECTROSTATIC AGGREGATION OF GRANULAR MATERIALS IN PLANETARY AND ASTROPHYSICAL SETTINGS

J. Marshall[1] and T. Sauke[1], [1]SETI Institute, MS 239-12, NASA Ames Research Center, Moffett Field, CA 94035-1000; jmarshall@mail.arc.nasa.gov.

Electrostatic forces strongly influence the behavior of granular materials in both dispersed (cloud) systems and semi-packed systems. These forces can cause aggregation or dispersion of particles and are important in a variety of astrophysical and planetary settings. There are also many industrial and commercial settings where granular matter and electrostatics become partners for both good and bad. This partnership is important for human exploration on Mars where dust adheres to suits, machines, and habitats.

Long-range Coulombic (electrostatic) forces, as opposed to contact-induced dipoles and van der Waals attractions, are generally regarded as resulting from net charge. We have proposed [1] that in addition to net charge interactions, randomly distributed charge carriers on grains will result in a dipole moment regardless of any net charge. If grains are unconfined, or fluidized, they will rotate so that the dipole always induces attraction between grains. Aggregates are readily formed, and Coulombic polarity resulting from the dipole produces end-to-end stacking of grains to form filamentary aggregates. This has been demonstrated in USML experiments on Space Shuttle [2] where microgravity facilitated the unmasking of static forces. It has also been demonstrated in a computer model (unpub.) using grains with charge carriers of both sign. Model results very closely resembled micro-g results with actual sand grains. Further computer modeling of the aggregation process has been conducted to improve our understanding of the aggregation process, and to provide a predictive tool for microgravity experiments slated for Space Station. These experiments will attempt to prove the dipole concept as outlined above [3].

We have considerably enhanced the original computer model: refinements to the algorithm have improved the fidelity of grain behavior during grain contact, special attention has been paid to simulation time steps to enable establishment of a meaningful, quantitative time axis, and calibration of rounding accuracies have been conducted to test cumulative numerical influences in the model. The model has been run for larger grain populations, variable initial cloud densities, and we have introduced random net charging to individual grains, as well as a net charge to the cloud as a whole.

The model uses 3 positive and 3 negative charges randomly distributed on each grain, with up to 160 grains contained within various size "boxes" that define the initial number densities in the clouds. Each charge represents a localized charged region on a grain, but does not necessarily imply single quantized charge carriers. The Coulombic equations are then allowed to interact for each monopole: dipoles and any higher order charge coupling is a natural product of these "free" interactions over which the modeler exerts no influence. The charges are placed on the surfaces of grains at random locations.

A series of runs was conducted for neutral grains that had a perfect balance of negative and positive charge carriers. Runs were also conducted with grains having additional fractional charges ranging between 0 and 1. By adding fractional charges of one sign, the model created grain populations in which all grains had excess charges of the same sign, giving the cloud an overall net charge. This simulates clouds subjected to ionizing radiation (e.g., protoplanetary debris disk around a protosun), or any other process of charge biasing in a grain population (e.g., in volcanic plumes). In another run series, random fractional charges of either sign were added to the grains so that some grains had a slight net positive charge while others had a slight net negative charge. This simulates triboelectrically-charged grain populations in which acquisition of an electron by one surface is at the expense of creating a hole elsewhere. This dual sign charging was applied in two ways: in one case the cloud remained neutral by ensuring that all grain excess charges added to zero; in the other case, the cloud was permitted slight net charge by not imposing a charge-balance condition.

Results of the model (Figs. 1 & 2) showed:

(1) The basic building block of aggregates is a chain structure produced by end-to-end dipole stacking of grains. This is unaffected by net charges (unless the charges exceed certain values, see 3).

(2) Neutral grains (and thus a neutral cloud) always result in the formation of aggregates which then cluster into one single large aggregate (Fig. 1): the cloud collapses into an electrostatic singularity.

(3) For grains with net charges of one sign, aggregates form by dipole attractions if the cloud has an initial high density, but the aggregates then disperse (Fig. 1). Large fractional net charges significantly inhibit aggregation; the

cloud is dispersed more or less as a population of single unattached grains. Aggregate size and morphology are dependent on the initial cloud density which controls the balance between the competing effects of attractive short-range dipole forces and repulsive long-range monopole forces.

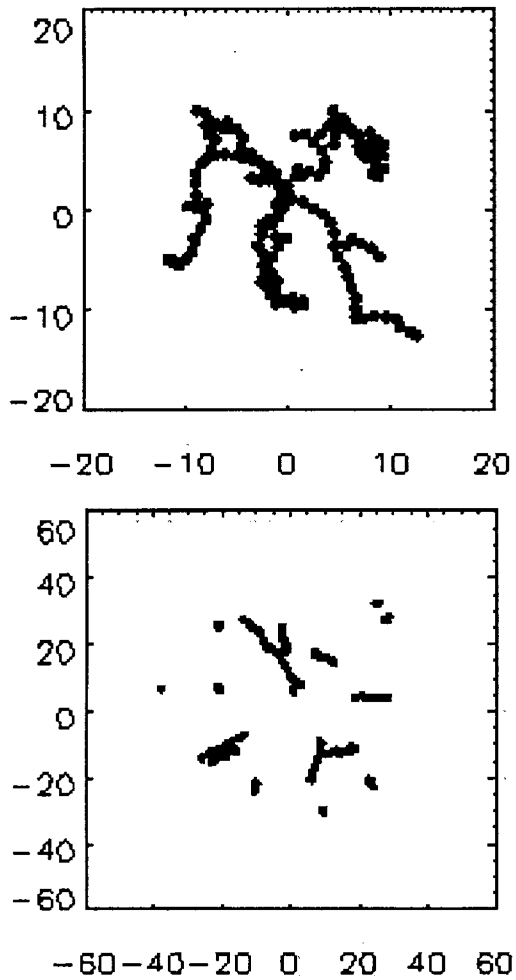


**Figure 1**: Upper figure shows computer-generated aggregate resulting from cloud collapse (neutral grains). Lower figure shows aggregates (formed by dipole interactions) in the process of being dispersed by monopole forces (net charge on cloud). Units = grain diameters.

(4) For grains with net charges of either sign, but with cloud neutrality, the cloud also collapses to a singularity, but a net charge on the cloud causes dispersion. Again, initial cloud density controls if it is large or small aggregates that get dispersed.
(5) The charged state of the cloud ultimately determines dispersion or collapse of the granular system. The charged state of individual grains (neutral, of one net charge, or of mixed charge) does not influence the overriding effects of the cloud's charge state, or the form of the basic chain-like aggregate building unit.
(6) In general, higher initial cloud densities permit the formation of larger, more intricately structured aggregates, such as might be expected in volcanic plumes. Lower initial cloud densities only permit the formation of small rod-like filaments that may be typical of aggregates in a dilute aeolian dust pall on Mars.

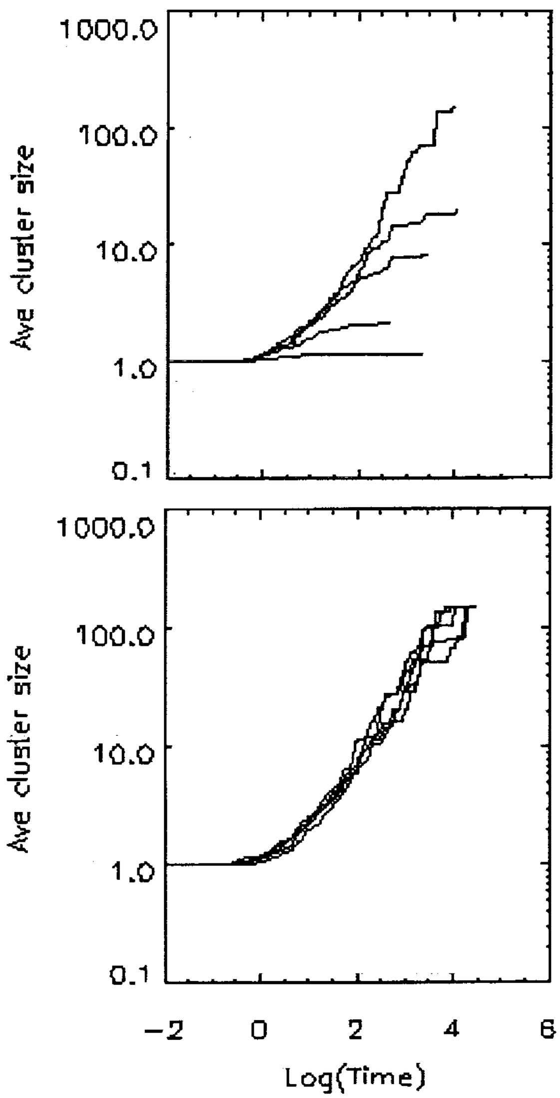


**Figure 2:** Figures show aggregate sizes (grains per cluster) in particulate clouds as a function of time. In upper diagram initially monodispersed grains all have net charge of the same sign: at max. charge imbalance (approximating one additional charge), grains disperse before aggregating (lowest curve). As imbalance decreases, larger aggregates form before dispersing, and in the limiting case of no net charge, clustering drives to a single large aggregate (no dispersion; top curve, also in lower diagram, left). In lower diagram, charge imbalance is constituted by positive and negative charges randomly distributed on the grains; the result is always clustering to a singularity. Interestingly, aggregation occurs at roughly the same rate regardless of the size of the net charge on individual grains.

**References**: [1] Marshall J. et al. (1998) 4th Microgravity & Fluid Phys. Conf. Cleveland. [2] Marshall J. (1994) NASA CP 3272, 717. [3] Marshall J. et al (1999) EGM Experiment, this volume.

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# "DUST DEVILS": GARDENING AGENTS ON THE SURFACE OF MARS, AND HIDDEN HAZARDS TO HUMAN EXPLORATION?

J. Marshall[1], P. Smith[2], B. White[3] and W. Farrell[4]. [1]SETI Institute, MS 239-12, NASA Ames Research Center, Moffett Field, CA 94035-1000, [2]Lunar & Planetary Laboratory, University of Arizona, Tucson, AZ 85721, [3]Mechanical & Aeronautical Engineering, University of California, Davis, CA 95616, [4]NASA Goddard Space Flight Center, MS 695.0, Greenbelt, MD 20771.

Dust devils are familiar sites in the arid regions of the world: they can produce quite spectacular displays of dust lofting when the vortices scavenge very loose dust from a dry lake bed or from recently disturbed agricultural fields. If one were to arrive at the center of an arid region, take one photograph, or even a series of photographs over a period of several days, then return the images for laboratory analysis, it would be most likely concluded that the region was inactive from an aeolian perspective. No images of general dust movement were obtained, nor were any dust devils "caught on camera" owing to their ephemeral and unpredictable appearance, and the fact that there was deceptively little residue of their actions. If, however, a camera were to take a 360 degree continuous recording over a period of a year, and the film were then to be shown at high speed over a period a several minutes, the impression might be that of a region ravaged by air vorticity and dust movement. Extrapolate this over geological time, and it is possible to visualize dust devils as prime aeolian agents, rather than insignificant vagaries of nature.

On Mars, the thin atmosphere permits the surface of the planet to be heated but it does not itself retain heat with the capacity of the earth's atmosphere. This gives rise to greater thermal instability near the surface of Mars as "warm" air pockets diapiritically inject themselves into higher atmospheric layers. Resulting boundary-layer vorticity on Mars might therefore be expected to produce dust devils in abundance, if only seasonally. The spectacular images of dust devils obtained by Pathfinder within its brief functional period on the planet testify to the probability of highly frequent surface vorticity in light of the above reasoning about observational probability. Notably, the Pathfinder devils appeared to be at least a kilometer in height.

There are several consequences for the geology of Mars, and for human exploration, if dust devils are to be expected in reasonable abundance. First, from a geological perspective, the vortices will act as "gardening" agents for the top few centimeters of entrainable material. Over time (hundreds of millions, or billions of years being available), they will cover the surface with scouring paths, and the grain sizes that can be lofted by a vortex probably extends over the whole sand to dust range. The depositional paths are, of course, much larger, so that vortex-induced deposition is more widespread than vortex-induced erosion, and will without doubt, affect the whole region in which the dust devils occur (this might explain why rocks at the Viking site seemed oddly capped with dust in a region apparently subject to general aeolian scouring). On Mars, the lift forces in dust devils might be less than on earth owing to the much thinner atmosphere, but this may be counterbalanced by lower gravity and greater vortex velocities. Certainly, when active, other aeolian phenomena on Mars --sand motion and dust storms, seem no less energetic and no less capable of lofting sediments than equivalent terrestrial aeolian phenomena.

Every several years, within the current climatic regime, the surface of Mars is subject to light dust fall from global dust storms. Over time, this should develop a very uniform surface layer, with commensurate uniformity in grain size, mineralogy, albedo, color, and general spectroscopic properties. Dust devils will disturb this situation by continually mixing the surface dust with underlying layers, perhaps composed of silt and sand. This size mixing will also involve compositional mixing. After some years, the thin layer of dust that may be difficult to entrain alone, becomes progressively mixed with coarser materials that could reduce the general aeolian threshold of the soil. Certainly the continual disturbance by vorticity will prevent surface stabilization that may bind or indurate grains (caused by slow cementation or ice welding at grain boundaries). If dust devils continually loft dust to kilometer heights, and the dust is sprayed into many cubic kilometers of atmosphere each time, could the devils produce a continual background of atmospheric dust that might be mistaken for the fallout of a distant large-scale dust storm?

From a human exploration perspective, dust devils are unlikely to pose any life-threatening situation for an astronaut unfortunate enough to encounter a momentary swirling cloud of loose soil. However, it is noted that pervasive dust is probably one of the greatest long-term hazards for a human encampment. The fineness and penetration capabilities of the dust, its electrostatic adhesive properties, and its complete ubiquity, render the material a persistent nuisance at best, but at worst, over a period of many months it is possible that space suits, machinery, habitat interiors, air filters, and so forth, could become jeopardized. Owing to dust penetration, the space suits used in the Apollo landings were rendered unusable after a few EVA activities.

There will be a definite attempt to situate a human colony on Mars in an area that is far removed from the regions of the planet known for being the centers of major dust storms. At the heart of these storm systems, the dust lofting mechanics are unknown, but they are energetic and perhaps potentially life-threatening for an astronaut. Locating a colony in a region that appears from space to be meteorologically benign may lead to colony placement in a region prone to dust devils, but dust devils are not (or have not been) detectable from orbital observations: the region surveyed for placement will appear like the apparently inactive arid area referred to earlier. The region may be spared from highly energetic weather systems, but it may not be necessarily immune from continual dust disturbance. Because dust devils occur in quiescent weather, and because they have capricious behavior, they could pose a hazard if the exploration strategy is ill prepared for their occurrence. The major effects of dust devils will be to contaminate machinery such as robotic or manned rovers, to deposit sudden pulses of soil into filtration systems that are pulling in martian atmosphere for fuel production, to deposit dust and grit on solar panel surfaces, and to generally exacerbate contamination effects already inherent in the dust. To this should be added the possibility of significant triboelectrical charging of air and dust in the vicinity of a dust devil. Again, it is unlikely to be life threatening, but it may be sufficient to create a voltage spike powerful enough to damage sensitive electronic equipment used for communications, guidance, and apparatus control functions. We note that terrestrial dust devils are electrically active, exhibiting an electric dipole moment, M, in excess of 1 C-m, corresponding to a charge density of $10^6$ e/cc in typical 100-m high, 20-m diameter structures. This charge density is nearly a factor of 1000 times greater than the average charge density in typical thunderstorms.

Since we know so little about dust devils on Mars, they may warrant further investigation in view of their potential role for aeolian geology over long periods. They could significantly affect any conclusions about surface processes on Mars drawn from spectroscopic data; these data will be a convolution of compositional signatures resulting from the "vorticity gardening" of the upper surface layer of the soil. From the perspective of developing strategies for human exploration of Mars, it might be important to allow contingencies for the phenomena of atmospheric vorticity, for vorticity with dust/sand lofting (dust devils), and for transient high-voltage electrical fields associated with the vorticity and/or soil disturbances.

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# THE ENIGMATIC LONGEVITY OF GRANULAR MATERIALS ON MARS: THE CASE FOR GEOLOGICALLY EPISODIC DUNE FORMATION

J. Marshall[1], [1]SETI Institute, MS 239-12, NASA Ames Research Center, Moffett Field, CA 94035-1000 (jmarshall@mail.arc.nasa.gov).

Martian sand dunes are concentrated in vast sand seas in the circumpolar belt of the planet's northern hemisphere, but they are also pervasive over the whole planet. Their occurrence is to be expected on a super-arid planetary surface subjected to boundary layer drag from a continually active atmosphere. Whilst their occurrence is to be expected, their survival is enigmatic. But the enigma only arises if the martian system is considered similar to Earth's --where sand is moved highly frequently, more or less on a seasonal basis. Experimentally it is readily demonstrated that active sand will soon wear down to small grains and eventually diminish to below the critical sand size required to sustain dune formation. According to conventional wisdom, sand moves at higher speeds on Mars than on Earth, and if it were to move as frequently as it does on Earth, then the dune-forming sand population should have long since disappeared, given the great longevity of the martian aeolian system (Sagan coined the term "kamikaze" grains to express this disappearance). No supply of sand could keep pace with this depletion, especially in light of the fact that Mars does not have very active weathering, nor significant crustal differentiation. On Earth, plate tectonics, magmatic activity, and general crustal differentiation over geological time have produced great concentrations of quartz crystals in the continental crustal masses. Not only are these quartz grains chemically and mechanically resilient, they are about the right size for being transported by either wind or water. Add to this, the geologically recent contribution of glacial grinding, and it is easy to see why there are dune field on Earth. So what are the martian dunes composed of, and how does the material survive the eons of attrition?

In addition to experimental demonstrations of sand comminution in laboratory aeolian simulations, the problem can be approached from first principles. Sagan [1] showed that by simple considerations of material strength versus mechanical work applied to the material, comminution to sub-sand size would be inevitable. Another semi-analytical approach might be taken by considering that the archetypal aeolian sand surface texture is an irregularly pitted ("frosted") surface composed of chipping hollows approximately 10 microns in diameter, 5 microns deep. Their volume = ~250 cubic microns, or about 1/25000 of the volume of a 100 micron diameter dune grain. Because a saltating grain always strikes another grain, then two surfaces are impacted. Thus each grain undergoes two impacts for every one saltation leap, when the impact statistics are considered for a closed dune system (it can be calculated that a grain can never undergo <1 impact, and never >2 per saltation leap). Hence, if we conservatively assume that there is damage to a grain each time it bounces, but with the minimum damage of only 2 microscopic craters per impact, then approximately 12,500 impacts are required to completely eliminate the grain. Of course, it would require only a fraction of this amount to reduce the grain to below sand size. A grain will make only several tens of saltation leaps on the stoss side of a dune before becoming buried on the lee slope. The dune then has to move its full length before the grain is exhumed again for abrasion. Even with this hiatus in transport, it is easy to see that terrestrial dunes need resupplying with sand in order to survive.

In recent theoretical work [2,3] it has been shown that martian aeolian transport may be initiated with high-speed grains, but this converts to a lower energy dynamic transport equilibrium in which a reptation population dominates grain transport (on Earth, at least half of the flux is by reptation and creep). On Mars, therefore, average grain speeds may be lower than those on Earth, or at least comparable. This would permit greater longevity for martian sands, but it would not go far enough to solve the survival problem. It may, however, explain why martian dunes are about the same size as terrestrial dunes. If martian saltation leaps were significantly longer than on Earth (as usually assumed), then a dune's lee slope would have to be correspondingly longer in order to trap the sand; this would scale up the whole dune structure. But with shorter trajectories in a reptation population, larger dunes would be unnecessary.

The problem of sand longevity would probably not be solved by assuming that dunes on Mars might be formed by aggregates of dust [4]. This ingenious concept allows for "grain" formation from fractal aggregates rather than from solid mineral material, especially in view of the potential for electrostatic charging and dust agglomeration on Mars. Additionally, the aggregates might roll as well as saltate with a much reduced aerodynamic threshold, and less disruptive impact forces. However, the aggregate idea potentially works for small drift structures no more than tens of centimeters depth. If we take a typical dune of 10 m height and assume conservatively that the porosity is 50% on average, and that the material is basaltic, we have a pressure at the base of the highest part of the dune of ~1.5 $kg/cm^2$; on Mars this reduces to 0.6 $kg/cm^2$. Laboratory tests show that dust material, aggregated or not, completely compresses to a highly compact material under these loads, and there is no preservation of any aggregate structures. Nor would any preservation be expected even if some aggregate were cemented. Dunes survive by reactivating sand grains that become exhumed on the stoss slope as the dune advances. If the dune had initially formed of aggregates it would be a single compressed mass, with no discrete sand-size units remaining to be exhumed. Other longevity concepts include very rapid re-supply from an essentially uncemented regolith that may never have been indurated by metamorphic and water-diagenetic processes as on Earth, or the idea that the sand grains are composed of a highly resistant material.

It is advocated here that all of the above arguments might supply some degree of mitigation to the attrition process, but ultimately, any theoretical or experimental data in support of survival will always be defeated by the vast time available for aeolian comminution on Mars. For this reason, it is proposed that if time is the problem, then time if likely to be the solution: sand mobility on Mars just does not occur as frequency as might be imagined from the pristine appearance of the dunes. At this point, it is noted that recent paleoclimatic discoveries about the Earth, show that our own planet is subject to heretofore unrecognized rapid and dramatic changes in climate. These are postulated to relate to ocean currents, for example, and so there is so there is no proper martian analog.

However, attention is drawn to this phenomenon because Earth's geomorphic systems may be more influenced by geologically transient "climatic catastrophism" than has been realized. The same might be true on Mars, with dune fields undergoing relatively brief episodic periods of major activity, then lapsing into protracted periods of aeolian stasis. The combined effect of a rotational precession of 175,000 years with an orbital precession of 72,000 years gives rise to 51,000-year long cycles of climatic change. There are also longer climatic episodes of 1,200,000 and 2,000,000 years. Whilst these may be gradual in cycling, it is noted that aeolian threshold is not gradual, by definition. Unless the wind energy exceeds a critical value, there will be no aeolian activity at all, regardless of the frequency or persistence of the wind. Thus, only at the peak of climatic change might there be significant aeolian activity. The scale of these periodicities in martian paleoclimate could extend the longevity of granular materials perhaps by as much as 4 or 5 orders of magnitude. The life of the dune systems would not just be extended by this reduction in attrition periodicity, it would be extended more perhaps by the increased time available for the production of new sand supplies that would await the ability to be mobilized into dune systems.

**References:** [1] Sagan C. (1973) JGR, 78, 4155. [2] Marshall J. and Stratton D. (1999) Abstract, this volume. [3] Marshall J. et al. (1998) LPS XXIX, 1131. [4] Greeley R. (1979) JGR, 84, 6248.

 

# COMPUTER MODELING OF SAND TRANSPORT ON MARS USING A COMPART-MENTALIZED FLUIDS ALGORITHM (CFA)

J. Marshall[1] and D. Stratton[1], [1]SETI Institute, MS 239-12, NASA Ames Research Center, Moffett Field, CA 94035-1000 (jmarshall@mail.arc.nasa.gov).

It has been postulated that aeolian transport on Mars may be significantly different from that on Earth [1]. From laboratory experiments simulating martian grain transport [2], it has been observed that (saltating) grains striking the bed can cause hundreds of secondary reptation trajectories when impact occurs at speeds postulated for Mars. Some of the ballistically induced trajectories "die out" and effectively join the ranks on the creep population that is merely nudged along by impact. Many of the induced reptation trajectories, however, are sufficiently high for the grains to become part of the saltation load (it is irrelevant to the boundary layer how a grain attained its initial lift force). When these grains, in turn, strike the surface, they too are capable of inducing more reptating grains. This cascading effect has been discussed in connection with terrestrial aeolian transport [3] in an attempt to dispel the notion that sand motion is divisible only into creep and saltation loads.

On Earth, only a few grains are splashed by impact. On Mars, it may be hundreds. We developed a computer model to address this phenomenon because there are some important ramifications: First, this ratio may mean that martian aeolian transport is dominated by reptation flux rather than saltation. On Earth, the flux would be a roughly balanced mixture between reptation/creep and saltation. On Venus, there would be no transport other than by saltation. In other words, an understanding of planetary aeolian processes may not be necessarily understood by extrapolating from the "Earth case", with only gravity and atmospheric density/viscosity being considered as variables. Second, the reptation flux on Mars may be self sustaining, so that little input is required by the wind once transport has been initiated. The number of grains saturating the boundary layer near the bed may mean that average grain speed on Mars might conceivably be less than that on Earth. This would say much for models of sand comminution on Mars.

A multiple-grain transport model using just the equations of grain motion describing lift and drag is impossible to develop owing to stochastic effects --the very effects we wish to model. Also, unless we were to employ supercomputing techniques and extremely complex computer codes that could deal with millions of grains simultaneously, it would also be difficult to model grain transport if we attempted to consider every grain in motion. No existing computer models were found that satisfactorily used the equations of motion to arrive at transport flux numbers for the different populations of saltation and reptation. Modeling all the grains in a transport system was an intractable problem within our resources, and thus we developed what we believe to be a new modeling approach to simulating grain transport.

The CFA deals with grain populations, but considers them to belong to various compartmentalized fluid units in the boundary layer. In this way, the model circumvents the multigrain problem by dealing primarily with the consequences of grain transport --momentum transfer between air and grains, which is the physical essence of a dynamic grain-fluid mixture. We thus chose to model the aeolian transport process as a superposition of fluids. These fluids include the air as well as particle populations of various properties. The prime property distinguishing these fluids is upward and downward grain motion. In a normal saltation trajectory, a grain's downwind velocity increases with time, so a rising grain will have a smaller downwind velocity than a falling grain. Because of this disparity in rising and falling grain properties, it seemed appropriate to track these as two separate grain populations within the same physical space. The air itself can be considered a separate fluid superimposed within and interacting with the various grain-cloud "fluids".

Spatially, we assume homogeneity in the x- (downwind) and y- (crosswind) directions, so the only spatial variations are z- (height) dependent. Since fluid (cloud and wind) properties' variations with height are most dramatic near the grain bed, a spatial binning is employed where the bin size increases with increasing height. We also expect that at any location in space, for rising and for falling grain clouds, there will be a distribution of grain velocities. The model therefore separates the grain cloud fluids into velocity bins. This provides a three-dimensional static model for the cloud of grains, with the dimensions being grain direction (rising/falling), height, and velocity. Each point in this 3-D static space has an associated velocity (x- and z-directions) and number density. The model's work is to evolve this static description through the "zero-th" dimension, time.

Time evolution of this system involves calculating interactions among the fluids, particularly between the air and the grain cloud fluids. These interactions are described by equations for gravitational settling, aerodynamic lift and drag, etc. Interactions between the static grain bed and the air, and those between the static grain bed and the flowing grain clouds, are described by empirically or semi-empirically derived relations. The gamma function velocity distribution used for grains aerodynamically lifted from the grain bed was derived by Anderson and Hallet [4]. The probability of an impacting grain bouncing from the grain bed, the velocity at which these grains bounce, and the velocity distribution of grains splashed from the grain bed by an impact were derived by Anderson and Haff [5]. It was therefore necessary to adopt a mixture of analytical and empirical yardsticks for our model, even though they do not appear in one universal transport model. We will ultimately determine if the "splash functions" we adopted are in accord with the cratering splash results obtained for Mars simulations in our earlier experiments [2].

The influence of the grain clouds on air velocity is an important interaction to consider because it provides the feedback mechanism whereby the density of the grain cloud influences the addition of new grains into the cloud. Initial conditions for the model set the threshold friction speed, $u_*$, from which grain-free air velocity profile is calculated by the law of the wall, $u_a = u_*/\kappa \ln(z/z_0)$, where $\kappa=0.4$ and $z_0$ is 1/30 of the grain diameter. Three forces are assumed to act on the air to influence the velocity profile: viscous shear, turbulent shear due to the grain bed, and drag from the grain clouds. Viscous shear is easily calculated from the dynamic viscosity and the air velocity gradient. In the absence of grain clouds, the total shear forces must yield the law of the wall velocity profile, producing a relation for the turbulent shear due to the grain bed, which remains constant in time because the grain bed remains essentially static. Combining these shear forces with the sum of the drag forces applied on the air by the grain clouds, the model can calculate the rate of change in air velocity at any height and any time.

A test of this model for Earth conditions used 0.3 mm diameter quartz grains (which have a critical threshold friction speed of 0.25 m/s), and a friction speed of 0.6 m/s. These conditions were chosen to match those used by Anderson and Hallet [4] for which they calculated particle trajectories. The maximum height for these calculated trajectories was ~3 cm, which agrees quite well with the fluid model results (Figure 1). Calculating the total mass flux for these conditions yields 0.004 and 0.008 kg/m/s using the relations given by Bagnold [6] and White [1] respectively. The fluid model produced a total mass flux at equilibrium of approximately 0.004 kg/m/s.

If one assumes the empirical and semi-empirical equations used in this model to be accurate, then a change in initial conditions should allow this CFA method to model aeolian transport on Mars and Venus as well as the motion of sand in flowing water. Figure 1 demonstrates promising results that are in accord our with analytical expectations about an initial burst of saltation that damps down to a more steady state after the reptation population has developed. It is important to note that the model is not structured in any way that by preconditioning, forces or facilitates our own expectations. Note that there are periodicities in the flux which we do not believe are model artifacts. These may be model representations of the causes of ripple formation. The fidelity of the model in replicating the Earth case provides us with sufficient confidence to apply the model to Mars and other grain/fluid mixtures. The model is a new approach, but it is currently generating only preliminary data that require substantiation by comparison with observations in nature.

**References:** [1] White B. (1979) JGR, 84, 4643. [2] Marshall J. et al. (1998) LPS XXIX, 1131. [3] Anderson R. (1987) Univ. Wash. Brownbag Preprint Series BB-56. [4] Anderson R. and Hallet B. (1986) GSA Bull., 97, 523. [5] Anderson R. and Haff (1991) Acta Mech., 1, 21. [6] Bagnold R. (1941) The Physics of Blown Sand and Desert Dunes, Methuen, London.

**Figure 1**: Terrestrial sand cloud developed by the CFA computer model. Moving from left to right is through time, but could also be envisaged as a snapshot of a saltation cloud developed in a wind moving in the same direction. The opacity of the cloud is that from 10 km. Note the initial pulse of aerodynamically lofted grains, and the fallout period before saltation and reptation evolve simultaneously. Abrupt grey levels are binning functions.

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# THE MECA PAYLOAD AS A DUST ANALYSIS LABORATORY ON THE MSP 2001 LANDER

J. Marshall[1], M. Anderson[2], M. Buehler[2], M. Frant[3], S. Fuerstenau[3], M. Hecht[3], U. Keller[4], W. Markiewicz[4], T. Meloy[5], T. Pike[2], W. Schubert[2], P. Smith[6]. [1]SETI Institute, MS 239-12, NASA Ames Research Center, Moffett Field, CA 94035-1000 (jmarshall@mail.arc.nasa.gov), [2]Jet Propulsion Laboratory, M/S 302-231, 4800 Oak Grove Dr., Pasadena, CA 91109, [3]131 Westchester Rd., Newton, MA 02458, [4]Max Planck Institute, P.O. Box 20 D-37189, Katlenburg-Lindau, Germany, [5]West Virginia University, Particle Analysis Center, 338 Comer Bldg., Morgantown, WV 26506, [6]University of Arizona, Lunar & Planetary Laboratory, Tucson, AZ 85721.

In a companion abstract [1], the "Mars Environmental Compatibility Assessment" (MECA) payload for MSP 2001 is described in terms of its capabilities for addressing exobiology on Mars. Here we describe how the same payload elements perform in terms of gathering data about surface dust on the planet. An understanding of the origin and properties of dust is important to both human exploration and planetary geology. The MECA instrument is specifically designed for soil/dust investigations: it is a multifunctional laboratory equipped to assess particulate properties with wet chemistry, camera imagery, optical microscopy (potentially with UV fluorescence capability), atomic force microscopy (AFM; potentially with mineral-discrimination capabilities), electrometry, active & passive external materials-test panels, mineral hardness testing, and electrostatic & magnetic materials testing. Additionally, evaluation of soil chemical and physical properties as a function of depth down to ~50 cm will be facilitated by the Lander/MECA robot arm on which the camera (RAC) and electrometer are mounted.

Types of data being sought for the dust include: (1) general textural and grain-size characterization of the soil as a whole --for example, is the soil essentially dust with other components or is it a clast-supported material in which dust resides only in the clast interstices, (2) size frequency distribution for dust particles in the range 0.01 to 10.00 microns, (3) particle-shape distribution of the soil components and of the fine dust fraction in particular, (4) soil fabric such as grain clustering into clods, aggregates, and cemented/indurated grain amalgamations, as well as related porosity, cohesiveness, and other mechanical soil properties, (5) cohesive relationship that dust has to certain types of rocks and minerals as a clue to which soil materials may be prime hosts for dust "piggybacking", (6) particle, aggregate, and bulk soil electrostatic properties, (7) particle hardness, (8) particle magnetic properties, (9) bulk dust geochemistry (solubility, reactivity, ionic and mineral species).

All of these quantities are needed in order for the human exploration program to make assessments of hazards on Mars, and to better enable the production on earth, of soil/dust simulants that can act as realistic test materials in terms of those properties that render dust a contaminant. Such properties include the small grain size that enables penetration of space-suit joints, mechanical interfaces and bearings, seals, etc., and presents difficulty for filtration systems. Size also plays a critical role in the potential for lung disease in long-term habitats. The properties of grain shape and hardness are important parameters in determining the abrasiveness of dust as it enters mechanical systems, or bombards helmet visors and habitat windows in dust-laden winds. Adhesive electrostatic and magnetic properties of dust will be prime causes of contamination of space suits and equipment. Contamination causes mechanical malfunction, tracking of dirt into habitats, "piggybacking" of toxins on dust into habitats, changes in albedo and efficiency of solar arrays and heat exchangers, and changes in electrical conductivity of suit surfaces and other materials that may have specific safety requirements regarding electrical conductivity. Other potentially hazardous properties of dust include the possibility of high solubility of some component grains (rendering them reactive), and toxicity of some materials --grains of superoxidants and heavy metals (there is always the slim, but not inconceivable possibility of biogenic components such as spores). Because Mars has no active surface aqueous regime, volcanic emissions, meteoritic debris, weathering products, and photochemical products of Mars have nowhere to go except reside in the surface; there are few mechanical or chemical (buffering) processes to remove the accumulation of eons.

From a planetology perspective, there are many enigmatic issues relating to dust and the aeolian regime in general. MECA will be able to address many questions in this area. For example, if MECA determines a particular particle size distribution (size and sorting values), it will be possible to make inferences about the origin of the dust --is it all aeolian, or a more primitive residue of weathering, volcanic emissions, and meteoritic gardening? Trenching with the Lander/MECA robot arm will enable local stratigraphy to be determined in terms of depositional rates, amounts and cyclicity in dust storms and/or local aeolian transport. Grain shape will betray the origin of the dust fragments as being the product of recent or ancient weathering, or the comminution products of aeolian transport --the dust-silt ratio might be a measure of aeolian comminution energy. Grain shapes, and the types of mechanical surface textures on grain surfaces (such as Hertzian, Boussinesq, conchoidal, blocky, or river fractures) provide clues about grain transport modes, and transport duration and energy. Some researchers have proposed that dune material on Mars may be sand-size aggregates rather than solid mineral grains. Certainly, it will be important to determine the aggregation and clumping tendency of the dust (aggregate shapes and packing densities) as indicators of the role that electrostatic meteorology plays on Mars in view of the unusual mixture of Paschen effects, superaridity, poor surface grounding, solar/cosmic ionizing radiation, and aeolian tribocharging of dust and atmosphere. Aggregation probably plays a key role in determining the rapidity of atmospheric cleansing after global dust storms.

How will MECA make all these determinations? At the beginning of operations, the robot-arm scoop will carefully excavate surface dust layers, but will eventually dig a 50 cm deep trench through the soil. If the walls of the trench collapse, we will acquire the knowledge that soil cohesion, induration, and bearing strength are poor, and that porosity is probably high. If the walls withhold, then stratigraphy (if present) will provide indications of dust/soil origin via horizons, depositional strata, concretions, duricrusts, etc. Patch plates on the arm will measure the abrasiveness of the dust and soil by the choice of a variable-hardness materials array (abrasion series). The MECA electrometer on the arm will measure charge buildup due to arm friction with the soil --indications of grounding and dielectric material properties. The electrometer will also determine ambient electrical fields, atmospheric ion populations, and soil-surface charges. These are all parameters that can be correlated with mechanical activity, wind speeds, aeolian threshold (if observed), and the potential for electrostatic dust aggregation. The RAC will roughly determine soil size distributions from boulder size down to fine sand/silt size. External passive materials arrays will determine the rate of dust accumulation on various natural and engineering materials as airborne particles settle from distant storms, or local dust devils. Electrostatic and magnetic patches are to be included in these arrays. Soil placed on the microscope stage will be subjected to shearing tests that determine scratch hardness, grain size and angularity, and smearing/streaking of minerals. Again, miniature patches arrayed around the stage will test for electrostatic and magnetic adhesion properties of the dust. The optical microscope will take over from the RAC in terms of magnification capabilities, and evaluate sand, silt, and dust fractions for particle size distributions, grain shapes, and aggregates and dust clumps (microscope magnification range 2.5 x to 25 x with stereo and confocal imaging capabilities). For the extremely fine dust materials (dust *sensu stricto*), the atomic force microscope (AFM) will enable imaging down to the nanometer level. A typical image can be tens of microns wide and with the same depth of field. The AFM functions with imaging capabilities comparable to an SEM, and will quantify dust grain size and shape distributions (from dust adhering to the microscope stage substrates). Grain angularity, crystal form, surface etching/weathering, microfabric, breakage, and particle microclustering can be evaluated for the most minute particles that comprise the martian soil.

One of the prime objectives of MECA is to utilize all of these data as input to the development of realistic Mars soil simulants. The JSC-1 Mars Simulant was developed for compositional and spectroscopic realism. MECA hopes to improve the fidelity of such simulants by amalgamating data on particle size distribution and electrostatic and magnetic properties of the martian soil. Grain size is a critical parameter when using a soil simulant to test the contamination of engineering materials, solar panels, and space suits. Soil particles become progressively more penetrating and progressively more adhesive as their size decreases and their electrostatic charge-to-mass ratio correspondingly increases. In general, dusts are very adhesive, and the amount present in the martian soil is an important value to acquire. When dust is inhaled, extremely fine particles can be exhaled again, while larger dust particles are short-lived in suspension and may never enter the lungs; it is dust particles of a particular intermediate size range that can pose a threat of lung disease to astronauts. At the other end of the size spectrum --in the coarse sand and grit grain population, data on grain size and angularity are important in terms of abrasion of materials by windblown sand. MECA will aim to provide soil-hazard indices based on combined data from grain size, adhesion potential, and mineral hardness.

The behavior of dust on Mars, in relation to humans or to the natural system, is intimately related to the electrical meteorology of the planet, and to the inherent electrostatic and magnetic properties of the particles. MECA provides for evaluation of these relationships through camera imagery, microscopy, AFM, materials testing, adhesion testing, and multi-functional electrometric measurements. The MECA wet chemistry data, in combination with synergistic data from APEX and DART MSP '01 experiments, should provide a wealth of information about ancient and modern clastic sedimentology of Mars.

**References:** [1] Marshall J. et al. (1999) MECA exobiology on Mars; abstract, this volume.

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# THE MECA PAYLOAD AS AN EXOBIOLOGY LABORATORY ON THE MSP 2001 LANDER

J. Marshall[1], M. Anderson[2], M. Buehler[2], M. Frant[3], S. Fuerstenau[3], M. Hecht[3], U. Keller[4], W. Markiewicz[4], T. Meloy[5], T. Pike[2], W. Schubert[2], P. Smith[6], [1]SETI Institute, MS 239-12, NASA Ames Research Center, Moffett Field, CA 94035-1000 (jmarshall@mail.arc.nasa.gov), [2]Jet Propulsion Laboratory, M/S 302-231, 4800 Oak Grove Dr., Pasadena, CA 91109, [3]131 Westchester Rd., Newton, MA 02458, [4]Max Planck Institute, P.O. Box 20 D-37189, Katlenburg-Lindau, Germany, [5]West Virginia University, Particle Analysis Center, 338 Comer Bldg., Morgantown, WV 26506, [6]University of Arizona, Lunar & Planetary Laboratory, Tucson, AZ 85721.

The "Mars Environmental Compatibility Assessment" (MECA) payload for MSP 2001 is comprised of a multifunctional laboratory equipped to assess martian soil properties with wet chemistry, camera imagery, optical microscopy (potentially with UV fluorescence capability), atomic force microscopy (AFM; potentially with mineral-discrimination capabilities), electrometry, active & passive external materials-test panels, mineral hardness testing, and electrostatic and magnetic materials testing. Additionally, evaluation of soil chemical and physical properties as a function of depth down to ~50 cm will be facilitated by the Lander/MECA robot arm on which the camera (RAC) and electrometer are mounted. MECA was designed as a NASA Human Exploration and Development of Space (HEDS) payload for determining the properties of martian soil that may be detrimental to human exploration. It is, however, well equipped to address exobiology questions in the following areas (Figure 1):

**Geochemical Clues To Aqueous Mineralogy and Oxidant Formation:** Using an array of ion-specific electrodes (ISEs), cyclic voltammetry, and electrochemical techniques, the chemistry cells will wet soil samples for measurement of basic soil properties of pH, redox potential, and conductivity. Total dissolved material, as well as targeted ions will be detected to the ppm level, including important exobiological ions such as $Na^+$, $K^+$, $Ca^{++}$, $Mg^{++}$, $NH_4^+$, Cl, $SO_4^-$, $HCO_3^-$, etc, as well as more toxic ions such as $Cu^{++}$, $Pb^{++}$, $Cd^{++}$, $Hg^{++}$, and $ClO_4^-$. MECA will enable surface versus subsurface material to be compared for these quantities. The role of water in surface processes is of course, key to the exobiological study of Mars; MECA wet chemistry essentially "reactivates" ancient aqueous settings. Although solution-dissolution dynamics are not always reversible, MECA will help constrain water soluble species in the soil that may have derived from ancient hydrothermal mineralization, from chemical precipitation in lake beds and carbonate-rich ocean basins, from flood waters episodically disgorged from the upper crust, or from moisture-driven mineral differentiation in the pedogenic surface. Counterbalancing the preservation of organic biodetritus potentially derived from a more clement martian past, are the postulated soil oxidants. These must be studied as key to carbon/life preservation for both extinct and potentially extant life on Mars. The oxidant issue is addressed by MECA by electrochemical detection techniques, while the targeted detection of compounds such as carbonates may be realized if reagent addition to the cells becomes a technical reality (currently under investigation).

**Soil Structures And Microfabrics As Indicators Of Water-Volatiles Migration:** Trenching with the robot arm and use of the MECA microscope and RAC will enable examination of soil layers, horizons, crusts, strata, nodules, and rock varnishes and rinds. These are clues to the migration of water in the soil. From such data may be inferred weathering rates, water volumes, thermal & wetting/drying regimes, and the general role of surface moisture on the planet. Examination of soil microscopically will enable aggregates/clods, grain packing, cementation structures, phyllosilicate cardhouse structures, and so forth, to be scrutinized. These features are important clues to soil porosity and thus to the transport of water and other volatiles through the martian surface which regulates the volatile budget of the atmosphere and polar caps [1].

**Minerals And Rocks As Clues To Ancient Hydrology:** Additional compositional information that can be cross-referenced with the wet-chemistry is obtained under the microscope from grain features such as cleavage, crystal shape, fracture patterns, grain color, grain surface coatings, pitting/etching, as well as from UV-excited fluorescence (by LEDs). MECA microscopy has dual magnification, 2.5x and 25x, and data-processing algorithms and image sequencing/offsetting to provide confocal and stereomicroscopy. Of exobiological interest would be the detection of calcite, dolomite, silica, fibrous evaporitic minerals, etc. Microscopy will enable discrimination (for millimeter-size fragments) of lithological species of exobiological interest such as amygdaloidal vesicular clasts indicative of hydrothermal activity, clastic sediments indicative of fluvial, lacustrine, or littoral activity, microlayered evaporitic materials, and so forth. Many lithic species betray aqueous or hydrothermal processes.

**Grain Textures As Indicators Of Aqueous Activity And Weathering:** AFM provides imaging capabilities comparable to SEM, and has resolution in the nanometer range. It will enable, along with microscopy, determination of microstructures such as those of the clay minerals (important indicators of water weathering), precise micro- and nano-scale mineral/grain shapes, and the surface textures of some of the larger grains. Sedimentologists routinely use mechanical grain-surface textures to evaluate transport history of sand grains, such as water or wind action [2]. Additionally, AFM enables imaging of chemical surface textures such as etch features, which are clues to weathering. MECA is hoping to use the AFM in a tapping mode so that phase-contrast imaging is available --this is an exciting new area of imaging with the potential for identification and mapping of mineral species, grain surface characteristics, and clast microfabrics.

**Figure 1: Potential MECA Observations For Exobiology On Mars.**

**MECA-APEX Synergism:** Various instrument packages on the Lander and Rover will work harmoniously and synergistically towards common science goals for both HEDS and planetary science. In recent commentary [3], the potential has been noted for deriving soil mineralogy and geochemistry by interaction of the APEX (ATHENA) payload elements of panoramic imagery, infrared spectroscopy, Moessbauer spectroscopy, and APX, with the suite of MECA techniques described above.

**References:** [1] Clifford S. and Marshall J. (1999) Abstract, this volume. [2] Marshall J. (ed.) (1987) Clastic Particles, Van Nostrand Reinhold. [3] Arvidson R. and Marshall J. (1998) Proc. AGU, Fall Meeting, F527.

**Figure 1: Continued.**

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# CHARACTERIZATION OF REGOLITH VOLATILE TRANSPORT AND STORAGE PROPERTIES BY THE MECA MSP 2001 LANDER PAYLOAD

S. M. Clifford[1] and J. Marshall[2]. [1]Lunar and Planetary Institute, 3600 Bay Area Blvd, Houston, TX 77058; clifford@lpi.jsc.nasa.gov., [2]SETI Institute, MS 239-12, NASA Ames Research Center, Moffett Field, CA 94035; jmarshall@mail.arc.nasa.gov.

The diffusive and adsorptive properties of the Martian regolith influence the exchange of volatiles between the atmosphere and subsurface [1-4]. Our quantitative knowledge of these properties is extremely poor –introducing substantial uncertainties in efforts to model long-term evolution of ground ice and diurnal, seasonal, and climatic cycles of CO2 and H2O. This situation should significantly improve upon arrival of the 2001 Mars Surveyor Lander in 2002.

In support of the Human Exploration and Development of Space (HEDS) enterprise, the 2001 mission will include a suite of instruments to characterize the nature of the Martian environment and assess whether it contains hazards that may threaten future human exploration. A major element of this effort is the Mars Environmental Compatibility Assessment (MECA) payload, which consists an optical microscopy system incorporating electrostatic, magnetic, and scratch-hardness materials testing palets, an atomic force microscope with imaging capabilities comparable to an SEM, a wet chemistry laboratory with four independent test cells, an electrometer on the robotic arm, material test patches, a camera also mounted on the arm, and a soil scoop for excavating down to about 50 cm into the soil. Although conceived to address the needs of HEDS, MECA payload is a sophisticated soil science laboratory that should provide a wealth of new data relevant to the volatile transport and storage properties of the regolith.

**Volatile Transport and Soil Structure**: A critical aspect of most attempts to model volatile transport within the Martian regolith is the assumption that its diffusive properties can be reasonably approximated by a soil of uniform pore size [5-7]. This simplification is only valid when the diffusing species is a non-condensable gas. For the case where the gas can condense and obstruct the pore network, the effect of pore structure cannot be ignored; most geologic materials possess a broad spectrum of pore sizes typically spanning 3-5 orders of magnitude [Figure 1]. When condensation occurs in such a system, it preferentially blocks the smallest (and most numerous) pores [Figure 2] --this can impede diffusive transport, and dramatically alter the resulting distribution of ice.

Pore size also affects how gaseous diffusion occurs. When the ratio of the pore radius to the mean free path of the diffusing molecules is large (i.e., $r/l > 10$), diffusion proceeds in response to the repeated collisions that occur with other molecules present in the soil pores. However, for very small pores ($r/l < 0.1$), collisions between the diffusing molecules and pore walls will greatly outnumber those that occur with other molecules (Knudsen diffusion). Because frequency of pore wall collisions increases with decreasing pore size, small pores can substantially retard diffusive flux through a soil. For pores of intermediate size ($0.1 < r/l < 10$), the contributions of both diffusive processes must be taken into account. Given the ~10 mm mean free path of H2O in the Martian atmosphere, and the pore size distributions of typical terrestrial clay- and silt-type soils, Fig. 1 suggests that plausible variations in soil structure can influence the diffusive exchange between the atmosphere and regolith by as much as 1-2 orders of magnitude.

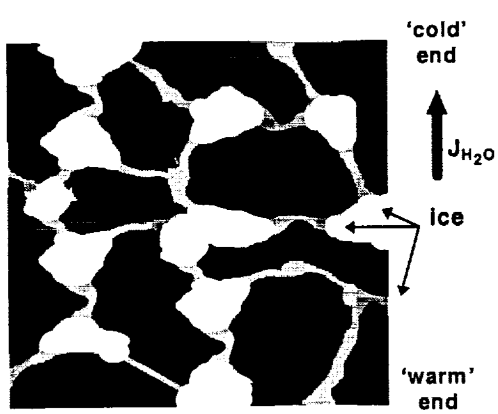
Gaseous diffusion is not the only process that contributes to transport of volatiles in the regolith. Experiments have shown that H2O and CO2 will be adsorbed on soil particles under Martian conditions. The presence of a concentration gradient within the adsorbed layer may induce diffusion on the inner surface of the pore walls. The magnitude of this surface flux is directly proportional to the specific surface area of the regolith, which increases with decreasing particle size.

Pre-Viking estimates of the specific surface area of the Martian regolith ranged up to several hundred m2 per gram, based on terrestrial analogs. Measurements by the Viking Lander gas exchange (GEX) experiment are consistent with a soil having a specific surface area of ~17 m2 g-1. Assuming uniform spherical grain size, and particle density of 2.65 g cm-3, this translates into a soil having a uniform particle diameter of 0.14 mm. Additional support for the presence of a fine-grained component in the regolith also comes from studies of the light scattering properties of dust suspended in the atmosphere, which are consistent with particle diameters in the 0.2 – 2.5 mm size range.

Given the regolith-forming processes that have likely been at work on Mars, it seems reasonable to expect particle size distribution of Martian soils to cover a broad range. Thus, the GEX results may well originate from the mixture of a small amount of very fine-grained, high-specific surface area clay(s) with a larger fraction of more coarsely-textured soil components.

Although the effective pore size of a soil with a broad spectrum of particles sizes may be determined by the smallest particle size present, this is only true in the limited case where the structure of the soil is single-grained and the volume fraction of small particles is sufficient to fill the voids between the larger particles. Indeed, particle size is only one of a number of potential factors that can influence soil structure. Others include particle shape and orientation, extent and scale of aggregation, and degree of soil compaction. As a result of the interplay between these various elements, a fine-grained illite can have a pore-size distribution closely resembling a coarse-grained kaolinite.

**Soil Data Anticipated from MECA**: The instruments that comprise MECA will assist modeling of the martian soil in regard to the aforementioned soil properties through acquisition of the following data:
(1) Camera, microscope, and AFM will, in combination, evaluate particle size distributions in the soil, and particularly of the surficial aeolian dust. Importantly, for considerations of porosity, where the significance of particles increases inversely with grain size, MECA instruments become increasingly quantitative. AFM will quantify both shape and size distributions of the grain sizes that "clog" the pores of the Martian soil. (2) Microscopy will determine the extent of aggregation of soil particles. It will observe if there are fractal clusters of grains electrostatically bonded by aeolian triboelectrification, physically bonded by solid-state diffusion at grain contacts, or mineralogically bonded by salt or iron oxide cementation. (3) Microscopy will define if various soil components are "clean" grains, if they have unaltered surfaces but parasitically adhering debris, if they are coated with salts and oxides, if they are weathered, porous, vesiculated, microfractured, and so forth --textures and microfabrics that define physical and chemical origins and properties of the soil such as porosity and reactivity. (4) Both microscopy and wet chemistry will constrain the mineralogy of the soil. This may define the presence of clays by AFM imaging of cardhouse structures, or by certain indications from the ionic species detected with the ISE arrays. Additional mineralogical data will be acquired through particle morphology, (possibly) through phase contrast AFM imaging of individual grains, by grain colors and fracture/cleavage modes, by examination of the soil under UV, by constraining magnetic and electrostatic properties of soil via the microscope and external patch-plate arrays, and by determining scratch hardnesses of soil components. (5) MECA wet chemistry will measure pH, redox potential, conductivity, and a wide variety of gaseous and dissolved substances (including chloride, nitrate, sulfate, carbonate, sodium, calcium, magnesium, carbon dioxide, oxygen, as well as number of other elements and compounds) --identifying potential cementing agents and freezing-point depressing salts. (6) The electrometer on the Lander arm will measure atmospheric ionization, local electric fields, and triboelectric charging of soil particles (significant in particle aggregation). (7) The Lander's robotic arm, scoop, and arm-mounted camera, will provide access to the shallow subsurface for sample retrieval and in situ imaging. Identification of possible soil horizons could have broad implications for understanding local physical, chemical, and volatile evolution of the surface.



**References**: [1] Leighton, R. B. and B. C. Murray, Science, 153, 136-144, 1966; [2] Smoluchowski, R. Science, 159, 1348-1350, 1968; [3] Fanale, F. P. and W. A. Cannon, Nature, 230, 502-504, 1971; [4] Fanale, F. P. and W. A. Cannon, JGR 79, 3397-3401, 1974; [5] Toon et al., 1980; [6] Fanale et al., Icarus, 67, 1-18, 1986; [7] Mellon, M. T. and B. M. Jakosky, JGR 98, 3345-3364, 1993; [8] Mellon et al., JGR 102, 19357-19374, 1997; [ ] Farmer, C. B. and P. E. Doms, JGR 84, 2881-288, 1979; [ ] Clifford, S.M. and D. Hillel, JGR 88, 2456-2474, 1983; [ ] Clifford, S.M., JGR 98, 10973-11016, 1993;

1999201892 (36/91 ABS. ONLY 417087 36 NNIF

# "EGM" (ELECTROSTATICS OF GRANULAR MATTER): A SPACE STATION EXPERIMENT TO EXAMINE NATURAL PARTICULATE SYSTEMS

J. Marshall[1], T. Sauke[1], M. Buehler[2], W. Farrell[3], R. Green[4], A. Birchenough[4], [1]SETI Institute, MS 239-12, NASA Ames Research Center, Moffett Field, CA 94035-1000 (jmarshall@mail.arc.nasa.gov), [2]Jet Propulsion Laboratory, MS 302-231, 4800 Oak Grove Dr., Pasadena, CA 91109, [3]NASA Goddard Space Flight Center, MS 695.0, Greenbelt, MD 20771, [4]NASA Lewis Research Center, MS 500-203, Cleveland, OH 44135.

A granular-materials experiment is being developed for a 2002 launch for Space Station deployment. The experiment is funded by NASA HQ and managed through NASA Lewis Research Center. The experiment will examine electrostatic aggregation of coarse granular materials with the goals of (a) obtaining proof for an electrostatic dipole model of grain interactions, and (b) obtaining knowledge about the way aggregation affects the behavior of natural particulate masses: (1) in unconfined dispersions (clouds such as nebulae, aeolian dust palls, volcanic plumes), (2) in semi-confined, self-loaded masses as in fluidized flows (pyroclastic surges, avalanches) and compacted regolith, or (3) in semi-confined non-loaded masses as in dust layers adhering to solar cells or space suits on Mars. The experiment addresses both planetary/astrophysical issues as well as practical concerns for human exploration of Mars or other solar system bodies.

The bulk behavior of dispersed, fluidized, or undispersed granular systems in terms of adhesive/cohesive properties, requires knowledge of the role of electrostatic forces acting at the level of the grains themselves. But when grains adhere to a surface, or they are in contact with one another in a stationary bulk mass, it is difficult to measure the forces acting on the grains, and the forces themselves inducing the cohesion and adhesion may be changed. Even taking a single grain for laboratory scrutiny, it is difficult, if not impossible, to define distribution and character of surface charging and three-dimensional relationships between charges.

The hypothesis that we will test on Space Station is that adhesion and cohesion of granular matter are mediated primarily by dipole forces that do not require a net charge; in fact, nominally electrically neutral materials should express adhesive and cohesive behavior. Moreover, the use of net charge alone as a measure of the electrical nature of grain-to-grain relationships within a granular mass may be misleading. We believe that the dipole forces arise from randomly-distributed positive and negative fixed charges on grains that give rise to a resultant dipole moment. These dipole forces have long-range attraction. Additionally, when non-conducting grains come into contact, there is sufficient local mobility of charges in the contact region to cause electron flow that generates a dipole effect across the junction. Random charges are created whenever there is triboelectrical activity of a granular mass, that is, whenever the grains experience contact/separation sequences or friction.

We have demonstrated in previous microgravity experiments that dipole forces give rise to the rapid conversion of particulate clouds into populations of aggregates, usually filamentary in form. Because filaments appear to be recurring building structures for aggregates, and because of their probable ubiquity in particulate clouds, they are worthy of study for this reason alone. However, both the filaments themselves and the way they respond to electrical fields provide valuable clues to electrostatic forces acting in granular matter. These clues provide insight into aggregation of grains, and adhesion of grains to various surfaces that is important to human exploration issues as well as to many fundamental scientific fields of study.

It is proposed that a good method of probing the electrostatic character of granular material, in a non-intrusive fashion, is to allow grains and aggregates to express their interactions through unconstrained motions (acceleration/drift rates, repulsions, attractions) while they are freely suspended under microgravity conditions as part of a dispersed cloud. The motions will be induced by controlled electrical fields and variable degrees of neutralization of the grains. Thus, dispersion and protracted suspension of grains will be our "tool" of choice for interrogating individual grains regarding their electrostatic properties. In particular, filamentary aggregation of grains in a cloud is a powerful tool for determining electrical polarization effects, and relationships between monopole and dipole forces, using growth rates, morphology, and in particular, the rotational and translational motions of aggregates as diagnostic expressions of the forces at work. Because different electrostatic forces cause different types of motion, this method enables each force to be isolated for study.

The experiment will be conducted in a series of eight self-contained modules of ~130 $cm^3$. Each will contain dielectric materials in granular form (e.g. quartz as 400 micron sand grains). The modules will have three basic configurations that enable attractive-repulsive forces between grains to be separated from one another; the forces can also be quantified in terms of magnitude, sign, and statistical variance.

The first module configuration enables an AC corona to develop inside the module. This produces positive and negative ions that will attach themselves to the free-floating grains. Thus, grains will have their surface charges neutralized and there should be no aggregation into filamentary forms, nor indeed, any long-distance attraction or repulsion between grains. However, grains will come into contact with one another as a result of random ballistic motion. Van der Waals forces, and contact-induced static forces should enable the grains to stick together, albeit very weakly; but aggregates should not be filamentary. This control test defines the nature of short-range contact forces and the role they play in aggregate morphology.

The second module configuration has a small (5-10 mm) metal ball held by insulating wire in the center of the module. The module will also be equipped with the charge-neutralizing corona capability. With the grains neutralized, an electrical potential will be applied to the ball. This will induce dielectric polarization in all the grains (there should be no filamentary aggregates). Because the electric field is inhomogeneous, all the grains will be attracted to the ball. Their rate of inward radial acceleration will determine the dielectric polarizability of the test materials and the force that is applied to a grain in response to any given field voltage. This experiment defines the dielectric induction role in aggregation in isolation from monopole and dipole effects. Notably, the drift rates should be very uniform.

This test will be conducted only after experiments with charged grains which subsequently have their charges progressively reduced by stepped application of the corona. Prior to neutralization, electrostatically charged grains will be dispersed in the module, allowed to aggregate into filaments, and then an electrical potential will be applied to the ball. The inhomogeneous field will ensure that all grains and aggregates with a dipole will be attracted to the ball once the materials orientate themselves into an attractive alignment. Both positive and negative potentials will be applied; the result should be the same. Differences will define a net charging bias in the grain population. Grains that have strong monopole components (large net charges) should be repelled under certain circumstances. Closer to the ball, the dipole effect may overwhelm the monopole repulsion. Importantly, the electrical field will induce dielectric polarization in all the grains that always acts as an attractive force. The mixture of dipole, monopole, and dielectrically-induced forces should produce a relatively large scatter in the rate of drift towards the ball (larger than for the neutralized grains). The form of the drift distribution curve for the grain population will enable conclusions to be drawn about relationships between all three forces. In one of the modules, the ball will be coated with a very thin non-conductive layer of material. This will not prevent the electrical potential from being "felt" by the surrounding grains, but it could fundamentally affect what happens to the grains once they touch the ball.

In the third configuration, the module is equipped with two electrically isolated metal plates on opposite walls, and a neutralizing corona as in the other two module configurations. A voltage applied between the plates produces an homogeneous electrical field that will have fundamentally different effects from the inhomogeneous field of the ball. When the grains have been neutralized and a voltage is applied, grains will be dielectrically polarized, but forces pulling the grains to the plates are equal and opposite at any point in the field, hence, no net movement of electrically neutral materials. The achievement of this condition defines the efficacy of the corona to neutralize charges on the grains, and will be used as a calibration test.

Similar to the strategy for the second module configuration, before grain neutralization (by varying degrees), grains will be dispersed, allowed to aggregate and come to rest in a quiescent state. When a potential is then applied to the plates, the dielectric effect has no manifestation (whereas in the second configuration, the dielectric effect only is observed).

With this third module configuration, we are able to study in controlled isolation, the respective roles of monopoles and dipoles. If aggregates are dipole structures --as postulated --they will orientate themselves in the field, causing preferred orientation of the aggregate population. The rate of rotation (torque) of a filamentary aggregate of any given length in any given field voltage defines the dipole moment of the aggregate, from which may be determined dipole strength. If filamentary aggregates orientate and then drift towards one of the plates, the rate of drift defines monopole strength or net charge on the aggregate (each of the dipole-bonded grains will have some small net charge, the sum of which will determine the drift). Thus, *torque* defines dipole strength, *drift rate* defines monopole strength, and *drift direction* defines monopole sign. Statistical distributions across the grain population for both dipole and monopole effects and their correlation (and the relationship between them and those for the purely dielectric-induction case) will define the degree of grain-population variability and be diagnostic of the presence and extent of the randomness of charging.

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# RADIO FREQUENCIES EMITTED BY MOBILE GRANULAR MATERIALS: A BASIS FOR REMOTE SENSING OF SAND AND DUST ACTIVITY ON MARS AND EARTH

J. Marshall[1], W. Farrell[2], G. Houser[2], and C. Bratton[1], [1]SETI Institute, MS 239-12, NASA Ames Research Center, Moffett Field, CA 94035-1000 (jmarshall@mail.arc.nasa.gov), [2]NASA Goddard Space Flight Center, MS 695.0, Greenbelt, MD 20771.

In recent laboratory experiments, measurements were made of microsecond radio-wave (RF) bursts emitted by grains of sand as they energetically circulated in a closed, electrically ungrounded chamber. The bursts (Figure 1) appeared to result from nanoscale electrical discharging from grain surfaces. Both the magnitude and wave form of the RF pulses varied with the type of material undergoing motion. The release of RF from electrical discharging is a well-known phenomenon, but it is generally measured on much larger energy scales (e.g., in association with lightning or electrical motors). This phenomenon might be used to detect, on planetary surfaces, the motion and composition of sand moving over dunes, the turbulent motion of fine particles in dust storms, highly-energetic grain and rock collisions in volcanic eruptions, and frictional grinding of granular materials in dry debris flows, landslides, and avalanches. The occurrence of these discharges has been predicted from theoretical considerations [1].

Grains of about 1 to 3 mm were circulated in a chamber 30 cm x 60 cm x 3 cm deep. The impelling air jet entrained material from the base of the chamber, piled the material against the opposite wall, then circulated it around again to the air jet. Spent air was vented through a vertical diffusion box above the circulation chamber, with a high capacity dust filtration system. The chamber itself was built of wood and other non-metallic materials so that it would act as an ungrounded system; this allowed build-up of triboelectric charge on the grains without grain-to-wall charge dissipation. Grain speeds were not directly measured, but estimated to be ~ 5-10 m/s at maximum. The RF pulses occurred when individual sand grains made contact with an ungrounded, high impedance antenna protruding into the experiment chamber. The internal *(in situ)* antenna was electronically configured to utilize the detected current as a trigger for an external receiving antenna. The external antenna was connected to an oscilloscope via a 10 MHz preamp. and used the triggering to hold the signal on an oscilloscope. The internal antenna was also connected to a second channel on the oscilloscope so that both waveforms could be displayed simultaneously. Temporal correlation of signals (confirming cause and effect between impact and RF radiation) could thus be made.

All grain populations were circulated for at least several minutes to permit surface charging through triboelectrification. No signals were measured from basalt grains or from quartz grains. Both materials are dielectrics (insulators). No signals were measured from copper grains -- a surprising result in view of copper's high conductivity. Nor were signals measured from ilmenite grains which are semiconducting. However, definitive signals were obtained from (dielectric) pyrite grains --a heavyside-exponential spike on the internal antenna and a very weak signal on the radiation antenna. The radiation signals lasted for ~ 1-2 microseconds and occurred exactly in conjunction with the large downward step of the contact-generated (*in situ*) signal. Magnetite (a semiconductor) generated large *in situ* signatures and very large RF signals in direct association with the impacts. The RF signature appeared more like the *in situ* signal with a fast rise and slow decay over the same time scale. Even when the antenna system was moved 10-15 cm away, RF signals remained readily detectable. With hematite (a dielectric material) we again saw large *in situ* impact signatures correlated with large RF spikes.

The experiments demonstrated that charge carriers are exchanged between grains and metal. We did not ascertain the direction of the exchange. Charges clearly exist on grain surfaces, and even non-conducting materials readily transfer charge; at present we can only surmise what the exchange mechanism is -- electrical arcing of high voltage surface charges, unusually high mobility of surface charges, or Fermi-level equilibration. Although we did not establish any correlation between RF and a particular class of conductivity (say, semiconductors), we note that all the observations were obtained from iron-bearing minerals. But with such a limited number of materials tested, the iron content may be coincidental. *Each material had its own RF signature*, thus suggesting that this can be used to compositionally discriminate between materials in flux. We note that Mars has a surface rich in iron-bearing minerals which makes them strong candidates for further investigation. Some of the best signals in our experiments were produced by the coarse-grained hematite. Large surface areas of coarse-grained hematite have recently been detected by Mars Global Surveyor.

It has long been realized that wind-blown grains in saltation clouds can become electrically charged [2]. Further, it has been noted that grain electrification and discharging is easier in a low pressure atmosphere such as that on Mars, but individual grains in a martian-like atmosphere may charge to as high as $10^4$ e [3]; both filamentary (long) and glow-like (short) discharges have been experimentally observed. Other laboratory experiments of martian grain charging noted significant electrical forces including the development of a greenish-white glow discharge [4]. It was suggested that such charged grains might remove biological organisms via an electrical "scavenging" effect. Recently, theoretical studies of dust-grain electrification and discharging [1] indicated that a VLF and HF radio based on current technology could detect *in situ* grain impacts together with an antenna listening for remotely-generated RF signals. Besides laboratory experiments, allegorical evidence exists for martian saltation cloud electrification and discharging. For example, terrestrial dust devils are electrically active, typically exhibiting an electric dipole moment in excess of 1 C-m [5,6]. Volcanic dust plumes are also electrically active. Discharges are commonly observed from these structures; charges can reach nearly 4kV/m [7].

For a grain of radius, a, and conductivity, s, the radiation frequency is $f = 1e^{11}$ s (in Hz) and radiation amplitude $E = 1.2\ e^9\ s^2\ a^2\ /r$ in V/m. So a single micron sized grain ($a^2 = 1e^{-12}$) of conductivity $s = 1e^{-4}$ mho/m ($s^2 = 1e^{-12}$) yields a signal strength at 1 m distance of $E = 1e^{-11}$ V/m for discharging to a "fast" surface. Given a highly conservative number density of 10 grains per cc in a dust cloud, the corresponding electric field 1 m from a cubic meter of electrified cloud is approximately 4 microVolts/m at 10 MHz. At 1 meter from a dust cloud containing 10,000 particles per cc, $E_{tot} = NE = 1e^{-7}$ V/m for each cubic centimeter. A 1-cubic m cloud generates 0.1 V. Regarding larger saltating grains, for 100 1-mm grains per cc, of similar conductance, E is $1e^{-5}$ V/m per grain. *For 100 grains per cc, in a 1 meter cloud, the fields exceed 100 V/m, suggesting that an entire saltation cloud on Mars ought to be in a coronal glow!*

Although the pulses are of low energy for single discharges, the total energy of RF released from a large grain mass could, in principle, be detected from a remote observing platform. The motion and composition of sand on martian dunes, or the turbulent energy of a dust storm might be discernible from an orbital platform or a Mars lander. The gravitational collapse of massive astrophysical dust/debris systems might also be discernible by radio telescopes in view of the enormous amounts of energy involved with such systems. Certainly, the activity of materials in volcanic eruptions on Earth could be detected by nearby ground stations. Experimental work is currently in progress to discern the signal characteristics of large numbers of simultaneous RF pulses that would be emitted by massive granular systems.

**References:** [1] Farrell W. et al. (1998) submitted to JGR. [2] Gill E. (1948) Nature, 162. [3] Eden H. and Vonnegut B. (1973) Nature, 280, 962. [4] Mills A. (1977) Nature, 268, 614. [5] Freier G. (1960) JGR, 65, 3504. [6] Crozier W. (1964) JGR, 69, 5427. [7] Anderson R. et al. (1965) Science, 148, 1179.

**Figure 1:** A typical antenna response from pyrite (mixed with quartz as a carrier grain population). The conducted signal (upper figure) is from the bare antenna impacted by the grains. The radiated signal (lower figure) is from an antenna external to the apparatus, and shows the radio pulse generated in response to the impact. Note exact time correlation, and unequivocal definition of signals.

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# INTERACTION OF SPACE SUITS WITH WINDBLOWN SOIL: PRELIMINARY MARS WIND TUNNEL RESULTS

J. Marshall[1], C. Bratton[1], J. Kosmo[2] and R. Trevino[2], [1]SETI Institute, MS 239-12, NASA Ames Research Center, Moffett Field, CA 94035-1000 (jmarshall@mail.arc.nasa.gov), [2]NASA Johnson Space Center, Code EC5, 2101 NASA Road 1, Houston, TX 77058.

Experiments in the Mars Wind Tunnel at NASA Ames Research Center show that under Mars conditions, space-suit materials are highly susceptible to dust contamination when exposed to windblown soil. This effect was suspected from knowledge of the interaction of electrostatically adhesive dust with solid surfaces in general. However, it is important to evaluate the respective roles of materials, meteorological and radiation effects, and the character of the soil. The tunnel permits evaluation of dust contamination and sand abrasion of space suits by simulating both pressure and wind conditions on Mars.

The long-term function of space suits on Mars will be primarily threatened by dust contamination. Lunar EVA activities caused heavy contamination of space suits, but the problem was never seriously manifest because of the brief utilization of the suits, and the suits were never reused. Electrostatically adhering dust grains have various detrimental effects: (1) penetration and subsequent wear of suit fabrics, (2) viewing obscuration through visors and scratching/pitting of visor surfaces, (3) penetration, wear, and subsequent seizing-up of mechanical suit joints, (4) changes in albedo and therefore of radiation properties of external heat-exchanger systems, (5) changes in electrical conductivity of suit surfaces which may affect tribocharging of suits and create spurious discharge effects detrimental to suit electronics/radio systems.

Material samples 3 cm diameter were placed in the Mars wind tunnel at two heights: 5-10 cm from the tunnel floor, and 50 cm from the floor. In the first position, the samples are in the boundary layer at the height of maximum sand flux during sand abrasion tests. In the second position, samples are in the freestream flow and experience maximum wind and dust speeds. Materials tested included those used for gloves and boots of space suits, various woven fabrics that form part of the suit structure, and helmet visor material. Tests were conducted at both Mars conditions of 10 mbar and Earth conditions for comparison. Mars soil simulants included (1) Carbondale Red --a powder of 1-2 micron particles composed of clays and silicates, (2) the JSC Mars-1 Simulant with a large grain size range (dust to coarse sand), also composed of similar materials, and (3) subrounded quartz sand of 100 microns to simulate dune materials. The hardness of quartz was not a distraction from simulation because of the relatively soft materials being impacted.

Experiments were conducted at ~10 m/s windspeed to simulate "nominal" conditions, with dust being artificially injected into the flow, and at threshold wind speeds of ~80 m/s, the lowest possible for simulating aerodynamic dust entrainment. Sand could only be meaningfully run just slightly above its threshold value of ~60 m/s (which would be somewhat less on Mars owing to lower gravity). The value of conducting tests at low pressure is not because of the grain motion energy, but mainly because the pressure creates low Paschen discharge potentials for electrostatic charges. It is these charges that are created triboelectrically by air and grain movement, and which are inherent in the electrostatic adhesion of dust. Further tests with a bell jar will assess the role of UV radiation, whose ionizing effect may cause changes in dust behavior.

Samples have been examined with a microscope-CCD camera that enables image comparisons by normalizing color enhancement. Video filming of the tunnel runs was also conducted. Additional examination techniques to be applied include profilometry and SEM of the surfaces to quantify abrasion and adhesion, respectively. We will also look at ways to remove the dust.

Observations made to date include the following:

**Materials Effects:** (1) PVC-based products used for gloves and boots are extremely prone to dust adhesion. (2) Fabric materials for the space suit body are also readily contaminated by dust adhesion, but Teflon fabric is much less prone to contamination than Gore twill fabric or composite Ortho fabric. However, within the composite Ortho weave, fibers composed of unit strands were uncontaminated while the composite strands became highly dust impregnated. (3) Helmet visor material became moderately contaminated with dust adhesion, but above acceptable limits for maintenance of transparency. (4) In general, it was observed that all materials (including metals and wood used in the sample mounting) become dust contaminated. (5) We have not attempted to remove the dust from the samples, so we do not know if the high velocity dust particles caused pitting beneath the dust layer. (6) Several months after the tests, the dust is still clinging tenaciously to the samples. This suggests a semi-permanent stable bond between surfaces and dust that is not changed by variations in temperature, humidity, nor long-term surface mobility of static charges. (7) All materials showed good resistance to the mechanical attack of sand grains. No obvious abrasion was apparent, but this needs to be better defined by profilometry/SEM. Fabric materials "curled up" as a result of the sand bombardment. The curling was outwards, suggesting that some elastic tension had been induced in the impacted side of the material, perhaps due to work-hardening of the plastic fibers.

**Dust Versus Sand Effects:** (1) Carbondale Red adhered to all samples with great uniformity. So too did the dust fraction of the JSC-1 Mars simulant. The coloration (and therefore, composition) of the dust was different in these two cases, but contamination was the same. Notable, the dust size that adhered from the very mixed size simulant was the same size as the particles that uniformly constitute the Carbondale Red. This implies that adhesion is primarily a grain-size function. Dust can be regarded as an adhesive substance, not simply fine granular material. (2) Abrasion effects from sand were not apparent, but in transmitted light, the visor appeared to have linear patterns perhaps suggesting dust accumulation in fracture lines. Interestingly, the main detrimental effect of the sand bombardment, especially on the visor, was to leave behind a layer of dust that was either scavenged electrostatically from the impacting grains, or acquired from comminution products of the grains. Sand acts as a carrier or supplier of dust, even if the grains themselves do little damage.

**Meteorological Effects:** (1) Low winds of about 10 m/s (such as those measured by Viking) produce extremely high levels of dust accumulation regardless of the dust flux values. For any given flux value, the thickness of dust accumulation is directly proportional to the sample's exposure time. When dust is settling out of the wind, accumulation or surface contamination develops in exactly the same way as gentle snow falling in windless conditions on Earth --build-up is proportional to time. (2) High wind speeds slightly above the dust threshold, produce contamination that is the opposite: it is independent of exposure time. Surfaces acquire a very thin, monolayer of dust that satiates the electrostatic coupling requirements of the material. Subsequent impact on that contaminated surface possibly adds dust grains, but also abrades away others so that a steady state is achieved. Apparently, surface-grain bonding is stronger than grain-grain bonding. Under the microscope, the surfaces seem to have been "painted" rather than "dusted" because the discoloration is so uniform and suggests something akin to electroplating or electrostatic bonding that occurs in printing and photocopying processes where fine carbon dust sprays uniformly to bond electrostatically to paper. The contamination is not removable by rapping the sample. As a result of the steady state condition achieved by the dust layer, there was no accumulation of thicker layers in hollows (e.g., in between fibers), nor any thinning of the layer on protrusions (e.g. on micro- and macro-asperities on the rough glove surfaces). (3) During tests of the visor material, vertically-mounted samples responded similarly under martian and terrestrial conditions; grains impacted the surface and bounced away into the wind. But for samples mounted at 15-20 degrees to the horizontal, the Earth-case sample retained a large population of "dancing" grains on its surface; grains were displaced by other incoming grains only to be captured themselves by a strong static charge. A steady state population was retained on the surface. This did not occur for the Mars case, suggesting that lower Paschen discharge voltages may have permitted charges to drain from the material. Sand was poured onto both the vertical and low-angled Earth-case samples once they had been removed from their mountings. All the sand slid off the material that had been vertical, but a completely uniform monolayer of sand was retained by the low-angle sample --a subtle, but as yet, unexplained triboelectrical phenomenon.

**Conclusions And Recommendations:** With heavy emphasis on the caveat that we do not yet know the effect of UV radiation, dust adhesion to Mars space suits is likely to be pervasive, and not easy to mitigate with current material candidates. Ionizing radiation on the Moon did not mitigate suit contamination. Once dust has reached a steady-state adhesive monolayer on materials, this layer is retained regardless of subsequent exposure to variations in soil particle size, wind speed, or other variables. Attempts to wipe off the dust will likely result in scratching of visor surfaces and further penetration of particles into fabrics. To mitigate contamination, it is recommended that the problem by circumvented whenever possible, rather than confronted, since there may not be easy solutions to preventing contamination. For example, for helmet visors, it is recommended that "peel-offs" be employed (as used by racing drivers). Disposable, thin plastic cling-film layers such as those used for food wrapping would also serve. For space suits, coveralls are recommended. A thin, lightweight, highly flexible oversuit would circumvent direct dust contamination. It would also avoid costly investment in attempting to develop static free materials, or dust resistant suit joints. Mars is an environment that should be treated as a contamination zone, with appropriate garments being applied. Space suits are primarily designed to be pressure vessels; pressure and dust problems are quite different issues whose solutions may be technologically complex if combined in one garment.